FASAC FOREIGN APPLIED SCIENCES ASSESSMENT CENTER
TECHNICAL ASSESSMENT REPORT

SOVIET ATMOSPHERIC ACOUSTICS RESEARCH

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August 1990

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The Foreign Applied Sciences Assessment Center (FASAC) is operated for the Federal Government by Science Applications International Corporation (SAIC) to improve U.S. knowledge of foreign applied science and to increase awareness of new foreign technologies with military, economic or political importance. Such knowledge can reduce technological surprise, can support estimates of the consequences of technology transfer, and can provide a background for U.S. research and development decisions.

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noise, background acoustic noise,
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sensing, microphone technology,
processing of acoustic signals, and
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ABSTRACT

The development of low observable air vehicles by the United States coupled with the historic propensity of the Soviet Union toward the defense of its borders raises the possibility of Soviet development of acoustic systems for detection and tracking of air vehicles as part of such defenses. This report reviews and assesses Soviet research in atmospheric acoustics. Topics considered relevant were aircraft noise, background acoustic noise, propagation, meteorological remote sensing, microphone technology, processing of acoustic signals, and acoustic-gravity waves and ionospheric detection. This study should provide an indication of the maturity of the Soviet technology base required for the development of potential acoustic detection and tracking systems.

Soviet research in aircraft noise is not as advanced as in this country though in certain areas of theory, individual Soviet scientists are doing leading research. Soviet studies of sound propagation from source to receiver, especially experimental work at low frequencies, is at the forefront worldwide. Soviet scientists continue to lead theoretical research in acoustic propagation through a nonhomogeneous atmosphere. Soviet remote meteorological sensing capabilities necessary to characterize acoustic propagation are unequalled. Most of the instrumentation and techniques necessary to sense and interpret acoustic signals from aircraft are evident in Soviet research. The imported and domestically produced microphones being used by Soviet scientists for outdoor measurements of sound are adequate. Soviet scientists currently possess all of the knowledge in the area of signal processing which is necessary to build an acoustic detection and tracking system with detection ranges far beyond the capability of aural detection by the unaided human ear. In addition, Soviet scientists are actively investigating upper atmospheric phenomena which may provide the necessary basis for aircraft detection schemes which involve local turbulence or upper atmosphere perturbations, though there is no mention of such detection schemes in the Soviet literature.

Overall, the Soviet technology base in areas required for acoustic aircraft detection and tracking is at least comparable to that in the United States, and, in some areas, more advanced.

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FOREWORD

This report, *Soviet Atmospheric Acoustics Research,* is one in a series of technical assessment reports produced by the Foreign Applied Sciences Assessment Center (FASAC), operated for the Federal government by Science Applications International Corporation (SAIC). These reports assess selected fields of foreign (principally Soviet) basic and applied research, evaluate and compare the foreign state of the art with that of the United States and of the West in general, and identify important trends that could lead to future applications of military, economic, or political importance. This report, like others produced by the Center, is intended to enhance US knowledge of foreign applied science activities and trends for reducing the risk of technology transfer, and also to provide a background for US research and development decisions. Appendix E of this document provides a list of titles of FASAC reports completed and in production.

The report was prepared by a panel of nationally recognized scientists and engineers who are active in atmospheric acoustics research. The panel membership is:

• Dr. Henry E. Bass (Chairman)	Professor and Director of the Physical Acoustics Research Center University of Mississippi
• Dr. Richard T. Lacoss	Director, Machine Intelligence Technology Group Lincoln Laboratory Massachusetts Institute of Technology
• Dr. Thomas E. Landers	Sensor Technology Group Electro-Mechanical Division Northrop Corporation
• Dr. Alan Powell	Professor Department of Mechanical Engineering University of Houston
• Dr. Richard Raspet	Associate Professor Department of Physics and Astronomy University of Mississippi

- Dr. James D. Revell — Acoustics Group
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On a part-time basis, over the period January to September 1989, each panel member devoted a substantial amount of time toward assessing the Soviet published research literature on atmospheric acoustics. The principal Soviet technical periodicals reviewed by the panelists are listed in Appendix C.

In addition to the panelists, Dr. Paul Neiswander and Mr. Bob Beavers of Northrop Corporation contributed their substantial expertise in analyzing Soviet capabilities in ambient acoustic background noise and microphone science and technology, respectively.

EXECUTIVE SUMMARY

A study of Soviet published research has been completed in areas relevant to atmospheric acoustics and aeroacoustics. The objective was to assess Soviet levels of knowledge and research that would support acoustic detection and tracking of military aircraft, beyond the usual aural detection capability of the unaided human ear. Specific topics considered relevant include: (i) aeroacoustic noise source modeling and sonic boom signatures of aircraft, (ii) atmospheric propagation, (iii) signal processing to enhance the signal-to-noise ratio at the receiver, (iv) microphone and sensor technology, and (v) background (ambient) noise studies.

The study indicates that Soviet scientists have a sufficient capability to design and deploy an acoustic detection system, and to predict mathematically the signal-to-noise ratio at the receiver, even though the Soviet Union lags the United States in computer hardware implementation, and has published far less in the various aspects of aircraft source noise prediction.

Although the Soviet Union has a long history of theoretical research in aeronautical acoustic sources, recent Soviet literature reveals surprisingly few original contributions and little experimental and applied research. There are some indications of large- and full-scale experimental facilities devoted to aeroacoustics, but there are virtually no publications describing this work. There seems to be an excellent but latent capability to model mathematically the most important aeroacoustic noise sources which is necessary to predict aircraft flyover noise signatures. Given sufficient priority, this capability could be improved and applied relatively quickly, probably without clear indications in the published literature.

The performance of potential aircraft detection schemes depends upon limitations imposed by background noise, especially at low frequencies. Soviet literature does indicate the ability to measure and model ambient noise levels. There is extensive work on acoustic noise related to health and hearing, but no Soviet work addresses outdoor ambient noise in the frequency range important for aircraft detection.

Prediction of system performance requires a thorough knowledge of losses along the propagation path. Soviet research on sound propagation at low frequencies, important to aircraft detection, indicates a level of experimental and theoretical effort greater than that found in the United States. Soviet scientists have conducted a series of field tests on meteorological effects on the long range propagation of low frequency sound. These have employed simultaneous meteorological and acoustic measurements as well as the comparison of experimental results with theory. Tests have been performed with pulsed and large-scale continuous wave sources. The work is of high quality and involves a number of very competent and widely respected scientists. The most likely motivation for the extensive research at frequencies of 10 to 30 Hz is to develop a database to support remote acoustic detection.

The Soviet Union has a very active program in the remote sensing of those meteorological properties important to predicting effects on sound propagation, using both SODAR and RAS (radio-acoustic sounding) systems. This program involves not only atmospheric research but also practical implementation (for sensing wind shears near airports). The sensing systems all employ modern real-time data processing.

The combination of work in acoustic propagation and atmospheric remote sensing has given Soviet scientists a unique capability to evaluate aircraft detection and tracking system concepts and to design systems which utilize real-time meteorological data.

The Soviet published literature seldom describes hardware developments in detail, but Soviet scientists report using microphones for outdoor measurements of sound. Some of these microphones are purchased from Denmark (the source of most high-quality microphones used in the United States), but some are manufactured in the Soviet Union.

Processors required to analyze received acoustic signals are not particularly sophisticated. Therefore, even though Soviet computer technology lags that of the United States, the Soviet Union appears to have the capability to develop the necessary processing systems for acoustic air surveillance systems. Basic algo-

rithms necessary for air surveillance are well known and appear in the Soviet literature.

The scope of this study was, to some extent, biased by the panelists' idea of how an acoustic aircraft detection and tracking system should or could look. In addition to conventional concepts, the possibility of using acoustic waves in the ionosphere to detect aircraft was examined. There is a very active Soviet research program in generation and propagation of acoustic gravity waves as well as in radiowave reflection from the ionosphere, but no mention of the application to aircraft detection was found in the Soviet literature.

Taken as a whole, the findings detailed in this report suggest that the Soviet Union has for many years supported research in those areas important for development of acoustic detection of aircraft. In some key areas, Soviet research surpasses the current state of the art in the United States. Continued development of acoustic systems for artillery location suggests that the Soviet Union has confidence in this technology and is able to produce rugged acoustic systems in large quantities.

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CHAPTER I
ASSESSMENTS

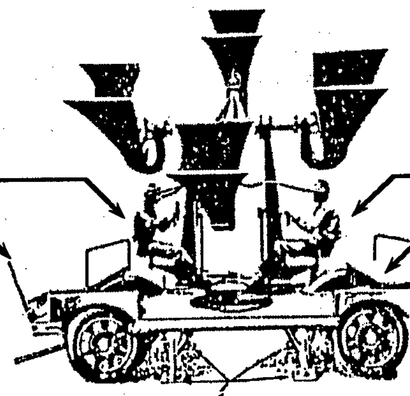
A. INTRODUCTION

Since World War II, air defense has depended upon increasingly sophisticated radar systems. The combined impact of anti-radiation missiles and nap-of-the-earth flying have challenged the capabilities of radar-based air defense systems. Faced with low flying attack helicopters and the potential deployment of US low observable long range bombers, the Soviet Union must be examining alternative air defense technologies. This study addresses one potential technology, acoustic detection, and attempts to assess the status of Soviet science in those sensor-related technologies thought to be important in the development of an acoustic system that would detect and localize airborne intruders.

The concept of acoustic warning systems in support of air defense is not new. The United States, England, Germany, and Japan had systems in place prior to World War II. Figure I.1 illustrates a US system. Though rather crude by today's standards, the basic components of modern acoustic aircraft detection are present in this early system. The large horns provide impedance matching between the human ear and the air (not needed in electronic systems). The wide spacing between horns provide the listener with an extended baseline for better bearing estimation. Aircraft identification is accomplished by a very sophisticated organic computer (a human).

With the discovery and rapid development of radar, research in acoustic detection of aircraft was virtually suspended in the United States for several decades. During this period, however, the basic science of atmospheric acoustics continued at a low level in US universities. In the Soviet Union however, scientists with a strong tradition of theoretical classical physics made significant advances in studies of outdoor sound propagation in the 1950s. Of special importance was the recognition of the vital role the ever changing atmosphere has on received sounds. In Germany, Kneser had earlier established that atmospheric absorption strongly depends upon humidity and dramatically favors low frequency propagation. The bending of sound by atmospheric temperature and wind gradients and scattering by atmospheric turbulence was well formulated by

1960. These results provided general guidelines for predicting the large variability in range and accuracy which is characteristic of an acoustic system.



The sound locator ascertains the angular position of the attacking aircraft and automatically transmits it to the comparator. To have range and accuracy and to enable the operators to distinguish between types of airplanes, the sound locator horns must collect all airplane sounds, especially the low pitched tones.

Figure I.1
Sperry Sound Locator, 1931[1]

The results of this theoretical research were consistent with the observed limitations of army acoustic artillery location systems. Due to variations in the atmosphere and terrain, these systems would at times work well but at other times provided a poor or no estimate of gun location even in the presence of a strong signal. The extreme sensitivity to local meteorology, combined with the inability to correlate signals from different guns, was responsible for a decline in the US use of artillery sound ranging systems. Although the theoretical basis for correcting for atmospheric effects was largely recognized in the scientific community, until recently there was no way to make the corrections necessary for tactical utilization. The computing power was not available. The availability of

1 Sperry Gyroscope Company, *Anti-Aircraft Search Lights and Sound Locator,* New York: June 1931, p. 39.

small computers has led to development of effective artillery location systems in the Soviet Union and Western Europe.

During the 1960s and 1970s, the United States developed an excellent capability to predict aircraft noise emission and propagation in the frequency range most important to noise control (50 to 10 kHz). The prediction capability was supported by an excellent base of experimental data collected near airports. At the same time, Soviet scientists studied industrial noise effects on workers. The concerted US effort in support of commercial aviation was not matched in the Soviet Union. Soviet research in the basic science and physioacoustics continued, but there were no large groups formed to develop quiet commercial aircraft.

From the 1960s through the 1980s, US aircraft noise prediction methods were developed that were suitable for the evaluation of commercial aircraft at low speeds ($M \leq 0.3$), but only for frequencies above 50 Hz (as was required for meeting US environmental laws). The NASA Aircraft Noise Prediction Procedure (ANOPP) was representative of the state of the art. More recently, interest in the United States has grown in acoustic detection of military aircraft at high subsonic speeds. For this purpose, there are many unknowns regarding noise prediction below 50 Hz and flight effects at high subsonic speeds. There remain uncertainties in propagation phenomena at long ranges over the entire acoustic spectrum.

In the late 1970s, reports of research combining meteorological and acoustic measurements began to appear in the Soviet literature. Remote sensing of the atmosphere was actively pursued at a number of institutes, placing the Soviet technology well ahead of the United States. Shortly thereafter, reports of low frequency, long range (up to 10 kilometers) sound propagation measurements appeared in the Soviet technical literature. Given the difficulties of organizing major large scale experiments in the Soviet Union, those measurements, made in a frequency range (10 to 30 Hz) of no interest to community noise, suggest potential military applications. These measurements appeared at roughly the same time that reports of an improved Soviet artillery sound ranging system with capabilities better than any US system began to circulate. This period also coincides with Soviet publications on condenser microphones suitable for military systems and visits to a premier manufacturer, Bruël and Kjaer in Denmark, to learn about microphone manufacturing technology.

The findings reported in the following chapters of this report suggest that the Soviet Union has, for a number of years, supported research in those scientific areas important for the development of the acoustic sensor element of detection barriers as part of strategic and tactical air defense systems. In key sensor technology areas, Soviet research is current and state of the art.

B. SUMMARY OF ASSESSMENTS

The development of low observable vehicles by the United States, coupled with the historical Soviet preoccupation with the defense of the homeland, raises the question of the possibility of Soviet systems for detection and tracking of air vehicles by, for example, acoustics. A study of Soviet published research in areas related to atmospheric acoustics and acoustic noise could provide an indication of the maturity of the Soviet sensor technology base required for the development of potential detection and tracking systems.

The notion of using acoustic detection barriers as part of an air defense system has been discussed in the US defense community for decades and the relevant technology areas have been identified. Particular areas of research relevant to the acoustic detection of air vehicles by defense systems include:

- acoustic signatures of air vehicles below 1 kHz (both subsonic and supersonic) and the determination of atmospheric properties which affect transmission of the emitted acoustic waves;
- investigations of the level and characteristics of natural and man-made atmospheric acoustic noise;
- atmospheric propagation of radiated air vehicle noise; and
- development of equipment and techniques for the detection, localization, and discrimination of noise sources in the atmosphere.

Each of the technologies necessary for air defense applications has other applications. For example, a thorough understanding of aircraft noise generation is necessary to design commercial aircraft that meet international standards.

This summary follows the general outline of the report, providing an assessment of Soviet science and engineering in air vehicle noise generation, propagation from source to receiver, acoustic receivers, and processing of received signals. The local atmosphere plays a major role in determining losses along the propagation path and the ability to localize a source. For this reason, Soviet capabilities in real-time remote sensing of the atmosphere have been included. Of special interest was any indication of research on detection approaches different from the standard microphone array. One such possibility, detection of acoustic-gravity waves in the ionosphere, is discussed below.

1. Aircraft Noise

To summarize very briefly, Soviet scientists possess strong talents in classical mechanics and mathematical physics which could be brought to bear on aircraft noise source prediction. However, their interest in aeronautical problems has not been sufficient to prevent a general marked lag in capabilities behind the West. There is relatively little experimental and applied research reported in the published literature, and practically none at full scale. This is also consistent with Soviet tradition; such reports are too few and are too scantily presented to provide a basis for inferring much about the extent or quality of the overall effort. But presumably enough has been done to provide at least the noise source prediction methodology applicable to new Soviet commercial aircraft in the take-off and landing modes. Given sufficient priority and the availability of extensive and rich Western published literature, it is likely that the Soviet Union could catch up quickly with the West in a relatively short time, that is, in just a few years; however, evidence of this is unlikely to appear in the published literature.

The sonic boom is a useful means of acoustic detection; however, Soviet researchers have published very little research in this area. Soviet scientists possess a basic understanding of the problem as well as a latent capability via their ability to calculate the steady supersonic flow past bodies of very general shape.

2. Background Acoustic Noise

Only a small amount of material exists in the Soviet literature relating to atmospheric ambient noise. Soviet researchers demonstrate considerable concern for noise as a health hazard. Most of the literature concerns the measurements of the loudness of noise from various man-made sources, and with noise-control mechanisms. Additionally, Soviet researchers appear to be concerned with infrasound from natural and man-made sources, with a strong emphasis on theoretical models. Soviet scientists also show the capability to measure and model atmospheric ambient noise. In summary, Soviet capabilities in the area of ambient acoustic background noise are equivalent to Western capabilities.

3. Propagation

Soviet research in atmospheric propagation has both strengths and weaknesses vis-à-vis the United States. Soviet scientists have more experience with normal mode solutions to the full-wave equation, as well as with theoretical treatments of refraction and scattering. This probably reflects the strong emphasis on mathematics in their educational system. The United States clearly has a much larger database for propagation in the audible regions, but the Soviet Union has more extensive controlled data in the 10 to 30 Hz frequency range. This latter frequency range is important to long range detection of aircraft. Further, research in this frequency range cannot be justified by concerns for community noise or aircraft certification requirements.

4. Meteorological Remote Sensing

The Soviet Union has a very active program in the use of acoustic and radio-acoustic sounding of the atmosphere. The Atmospheric Physics Institute of the Soviet Academy of Sciences in Moscow has a very active program in the use of sounders for atmospheric research and for sensing of wind shears around airports. The sensing systems all employ modern real-time data processing.

Although the Soviet Union lagged the West in remote meteorological sounding in the 1970s, it appears to have caught up with the West and may lead

in the practical application of sounders for measurement and wind shear detection. Scientists at the Atmospheric Physics Institute work on the measurement and prediction of low frequency sound, as well as atmospheric physics. The potential exists for pioneering research and application of meteorological sensing to real-time predictions of propagation conditions.

5. Microphone Technology

A difficult portion of any acoustic detection system is the microphone. In general, at least some of the microphones must be designed to operate in all weather conditions, where both high humidity and high temperature service can be expected. They may also need to survive radiation effects. These factors suggest that typical electret condenser microphones (which are usually employed because they have excellent sensitivity to weak acoustic signals) may not be the best choice under the adverse environmental conditions described above. Also, conventional condenser microphones operating under these conditions would require an expensive, complex dehumidifier. Based upon these considerations, a piezoelectric-type transducer could be used. The Soviet published literature contains a substantial number of references to piezoelectric devices for industrial use, so it is reasonable to assess that the Soviet basic technology and manufacturing capabilities in this area are very good. Soviet researchers have described microphones in their published literature for at least 40 years. For the same length of time, Western researchers have described all significant advances in the basic science and manufacturing technology in the Western published literature. In summary, in the area of microphone technology, it is reasonable to expect that the Soviet Union has capabilities that are equal to or perhaps ahead of Western capabilities and that are more suitable for use in acoustic detection systems.

6. Processing of Acoustic Signals

The state of Soviet signal processing technology is sufficient to support the development of ground-based acoustic air surveillance systems. Basic algorithms are well known and would not be a limiting system development factor. Cost-effective real-time implementation is probably more of a limitation but is well within the present Soviet technological capabilities. Digital implementa-

tion, using integrated circuit chips comparable to those available in the United States in the middle to late 1970s, appears to be the best technology option available to the Soviet Union. Optical (analog) processing might also be considered, but optical processors are probably better suited to applications that require much more processing power and can justify the cost of optical processing systems.

Some additional points are also important to note. First, the required signal processing technology is not particularly demanding or highly specialized for this problem. There are many elements in common with underwater acoustic surveillance and passive electromagnetic surveillance systems. The details are different for the different applications, but the basic algorithms and concepts are similar. Second, it would have been surprising to find much Soviet literature with an explicit connection to aeroacoustic surveillance. This is a tiny application area. Even in the United States and Europe, where we know there is research, there is very little literature available with explicit reference to the aeroacoustic surveillance application. US security guidelines would prohibit publication of an overly-explicit description of such work and the same can be presumed of the Soviet policies.

7. Acoustic-Gravity Waves and Ionospheric Detection

It is well known that low altitude acoustic sources produce gravity waves which perturb the ionosphere. These perturbations can be detected by Doppler shifts in radio waves reflected from the ionosphere. Whether these phenomena can be used for aircraft detection is not clear, since the ambient noise levels in the ionosphere are quite high.

It is clear that the Soviet Union is very active in ionospheric research and that this research is well supported. Four major institutes are involved in the detection of ionospheric disturbances. There is much activity on the theoretical prediction of the generation and propagation of acoustic gravity waves and on radio wave reflection from the ionosphere. If this phenomenology can be exploited for aircraft detection, the Soviet Union has the necessary manpower and capability to do so. The Soviet Union clearly leads the United States in this field of research.

C. FUTURE DIRECTIONS AND INDICATORS

The Soviet Union has capabilities in all the technical areas important to acoustic aircraft detection.

A strength of Soviet research is remote sensing of atmospheric properties important to propagation predictions. If the Soviet Union were to field acoustic systems with accompanying remote atmospheric sensors, then one might believe that Soviet researchers could correct for atmospheric effects in real time. Such integrated systems might appear in artillery sound rangers or systems designed to detect helicopters. Finally, the demonstrated Soviet ability to field an acoustic artillery detection and localization system in a military environment would argue in favor of Soviet confidence in the sensor and system technology needed for the air defense application. A thorough study of modern Soviet sound ranging systems and sonar systems would be beneficial is possible.

Soviet efforts in developing quiet aircraft and substantiated signature prediction capability will require a more coordinated approach in order to be successful. Based upon current literature, one should not expect to see innovative quiet techniques emerge from the Soviet Union in the next decade.

The strong research team at the Atmospheric Physics Institute should continue to publish combined meteorological and acoustic data. In the future, we should expect to see data and theory which include effects of irregular terrain. If the group continues to receive very high priority, computer-intensive calculations which include turbulence can also be expected. Given the strong theoretical support and current experimental systems, the Soviet Union should continue to be a leader in propagation predictions.

Based upon Soviet capabilities and potential economic benefits, we should expect to see improved microphones produced in the Soviet Union (or in Eastern Europe). These will quite possibly be based upon modern SiO_2 technology.

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CHAPTER II
AIRCRAFT NOISE

A. SUMMARY

In the Soviet Union there is a very wide understanding of practically all the varied fundamental aspects of acoustics, fluid mechanics, and the interdisciplinary aeroacoustics which bear, or could be brought to bear, on the noise sources of air vehicles. Most of this understanding is on a somewhat detached mathematical plane, and much of it is at a sophisticated level. As far as can be determined from the few overly brief papers (with very few exceptions), the relatively small amount of experimental work reported seems to be carefully chosen and competently executed within the limits of sparse equipment and facilities. This bias towards applied mathematics is, of course, quite consistent with the long-term nature of Soviet basic science as a whole.

The inherent Soviet capability to solve, at the basic research level, practically any air vehicle noise problem that could be posed is judged to exist (limited only by supercomputer availability); but that potential has evidently not yet been tapped.

A significant fraction of the talent is widely dispersed organizationally and geographically, and overt indications of aeronautical interest are relatively rare. The interests of the early Soviet theoretical pioneers in addressing aeronautical noise problems seems not to have been exploited. The result is that since the early 1950s, there have been surprisingly few original Soviet contributions addressing the aeronautical noise field; and in all but one or two specialized aspects (that is, vortex acoustics and possibly boundary layer noise), the lag continues. Judging from the published literature, Soviet interest in shock-generated noise and the supersonic boom is practically nil, despite a very strong traditional and continuing capability in theoretical shock-wave dynamics.

There is only very occasional evidence of cooperative efforts, for example, between the Siberian Division of the Academy of Sciences and the Aerohydrodynamics Institute im. N. Ye. Zhukovskiy. There is a frequent apparent obliviousness to similar work elsewhere in the Soviet Union (sometimes even in the

same research institute!), and in the West. In the two major research centers—the Zhukovskiy Aerohydrodynamics Institute and the Acoustics Institute im. N. N. Andreyev—this lack of cooperation may mainly reflect the personal attitudes of the authors, but in the case of the rest, it also reflects upon very inadequate library resources. (On the other hand, the occasional review article by an author from a major institute is very thorough and displays a keen awareness of worldwide literature.) One has the impression that much, though certainly not all, of the theoretical research reviewed reflects the individuals' own research interests, rather any guidance or interest towards contributing to solving real problems.

If one takes all the basic research which could be applied to the subject area, though from diverse origins and technical areas, most of the underlying principles of air vehicle noise have been addressed to some degree in work of high quality. Yet, even on this basis, the total volume of Soviet literature is only a small fraction of that of the West.

The published literature contains a very limited amount of research apparently directed at applications, and is almost barren when it comes to full-scale investigations. For the mission-oriented Zhukovskiy Aerohydrodynamics Institute, one is tempted to infer that applied research in aircraft noise has received minimal priority over the long term. However, there are a few indications that more information exists than has been published, which has to be the case if new Soviet commercial aircraft are to meet international noise requirements. This could simply reflect the usual scarcity of reports from the large Soviet mission-oriented institutes.

There appears to have been some attempt to pull things together through the publications of collected works (notably a series of four publications by A. V. Rimskiy-Korsakov of the Andreyev Acoustics Institute) and symposia on aircraft noise, in which A. G. Munin of the Zhukovskiy Aerohydrodynamics Institute usually figures. Most of the papers with an applied flavor appear in these works or conference proceedings. However, they are all in Russian and are not made readily available, probably even to Soviet researchers.

The prognosis is that the published literature will show evidence of continued scientific progress along the same general lines and that there will be scant evidence of engineering applications, whether or not these are being pursued energetically.

The relatively recent availability of funding to the research institutes of the Soviet Academy of Sciences from the "industrial sector" may have some influence in encouraging more relevance, but only if the latter perceive some priority in the aircraft noise source area and the reward system changes.

However, if given modest priority in the system, the work could have greater impact, for example, through greater mobility between organizations, especially between the research institutes of the Soviet Academy of Sciences and the mission-oriented Zhukovskiy Aerohydrodynamics Institute, as already seems to exist in the boundary-layer control area.

Given high priority, involving institutes not normally associated with aeronautics, and the provision of adequate funding for experimental and more full-scale investigations, the impact could be very significant.

Certainly rapid and significant progress has been made by Soviet researchers in submarine silencing, according to US news releases, implying a focused effort in research from the basic through to full scale application. It should be noted that while a small number of articles in the published literature on basic boundary layer noise research clearly address marine applications, there is really no hint at all in the published literature of the huge amount of even the basic research which must have been undertaken (while the applied and developmental work would not be expected to receive much press anyway). For this reason, a note of caution must be attached to the foregoing conclusions.

Soviet researchers have a respectable capability for calculating the steady supersonic flow about aircraft and space vehicles of general shape. This is a necessary prerequisite for predicting sonic boom signatures. The Applied Mathematics Institute im. Keldysh could be judged to be on a par with the United States as far as the understanding of computational fluid dynamics (CFD) methods; however, this same capability is widely dispersed in the United States among all

of the major aerospace firms, universities, and research institutes. Based on the sheer volume of Western publications, it is tempting to say that the Soviet Union is behind the United States regarding CFD methods to define the supersonic near flow-field as the starting point for a sonic boom signature.

Regarding computing hardware and software capabilities, it appears that the influential Soviet researchers have access to sufficiently powerful computers for solving the inviscid flow field about vehicles of almost any shape which is required. If the Soviet Union ever catches up with the United States in hardware, it could become more competitive than the United States in CFD because of its strong educational background in pure and applied mathematics.

The paucity of Soviet publications on the sonic boom problem somewhat parallels the significant reduction in sonic boom research in the United States and the United Kingdom (UK) since roughly 1970. It is our conjecture that this situation can be mainly attributed to a sense of futility based upon the inability of environmental regulatory agencies to establish an "acceptable level" of sonic boom overpressure.

To summarize very briefly, the Soviet Union has strong capabilities in basic theoretical research which could be brought to bear on air vehicle noise source prediction; but the interest in aeronautical problems has not been enough to prevent a general marked lag behind the West. There is relatively little experimental and applied research in the published literature, and practically none at full scale. This is also consistent with Soviet traditions: the research is too sparse and poorly reported to provide a basis of inferring much about the extent or quality of the overall effort. But presumably enough has been done to provide at least the noise source prediction methodology applicable to new Soviet commercial aircraft in the take-off and landing modes. Given sufficient priority and the availability of the extensive and rich Western published literature, it seems feasible that this inferred minimum level of prediction capability could be greatly embellished in a relatively short time; evidence of this may not immediately appear in the published literature.

B. OVERVIEW

The subject of aerodynamic noise has very early origins, although a thorough understanding of the mechanics has only come about fairly recently. Sondhauss in 1854 gave a good description of the edge tone, in which a thin laminar jet blows onto an edge and produces audible discrete frequencies, even though there is no mechanical vibration and no resonator. But over a century was to pass before the pertinent acoustic and fluid instability characteristics were melded to produce a reasonably complete aeroacoustics theory. Strouhal's experiments (1878), also in Germany, showed that the aeolian tone which occurs when wind blows over a cylinder—for example, a telephone wire—has its frequency proportional to the wind speed, and inversely to the diameter, though it was Rayleigh who made the critical observation that the tone existed even if the wire did not vibrate. These are the classic examples of noise generated aerodynamically—vibrations of solid surfaces are not essential to the production of sound; the same is true of jet noise, where the noise is generated by parts of the jet well removed from the exhaust pipe. This was pure research, motivated by scientific curiosity, and Germany held the prime position.

Aircraft noise, due to propeller and engine exhaust, was first studied in England in connection with sound location just after World War I, but the first theory for propeller noise based upon principles later shown to be fundamentally correct was by the Soviet researcher Gutin (written in 1936 but not available in the West until 1948). He was familiar with the earlier British work, and supposed that the rotating propeller exerted oscillatory forces on the surrounding atmosphere, giving rise to the distinctive periodic sound. Yudin, in a 1944 paper, hypothesized, similarly and also correctly, that the higher frequency aeolian tones emanating from a rotating rod (like the "swish" of a golf club and used to simulate vortex noise of a propeller) were caused by the reaction of the aerodynamic force on the non-vibrating cylinder acting on the medium. Blokhintsev produced his monograph, *Acoustics of a Nonhomogeneous Moving Medium,* in 1946, very comprehensive in its day but unknown in the West until a decade later. This work appears to be the starting point for much of the subsequent Soviet theoretical research, bearing on flow noise and moving sources. It also includes an account of Obukov's fundamental work of 1942 on the scattering of sound by turbulence. Obukov used a technique paralleling one

used by Rayleigh in his scattering theory, but Rayleigh's pertinent works appear to be unknown in the Soviet Union at that time. Thus, the Soviet Union had the leadership position just after World War II, stimulated, presumably, by the same military need which spurred the earlier British work.

In 1950, the British Ministry of Supply captured Lighthill's interest when it became concerned about the potential noise problem of jet aircraft operating from airfields surrounded by dwellings. Lighthill published the pioneering theory of aerodynamically generated sound in 1952.

The most efficient sound source is the simple one, a monopole, as for a small sphere vibrating in its *first mode,* that is, fixed in position, but oscillating in radius (see Figure II.1). Obviously, it radiates symmetrically in all directions. The pulse jet (similar to the buzz bomb engine of World War II) was considered to have potential for tip-driven helicopters, but the powerful monopole radiation completely negated this design concept.

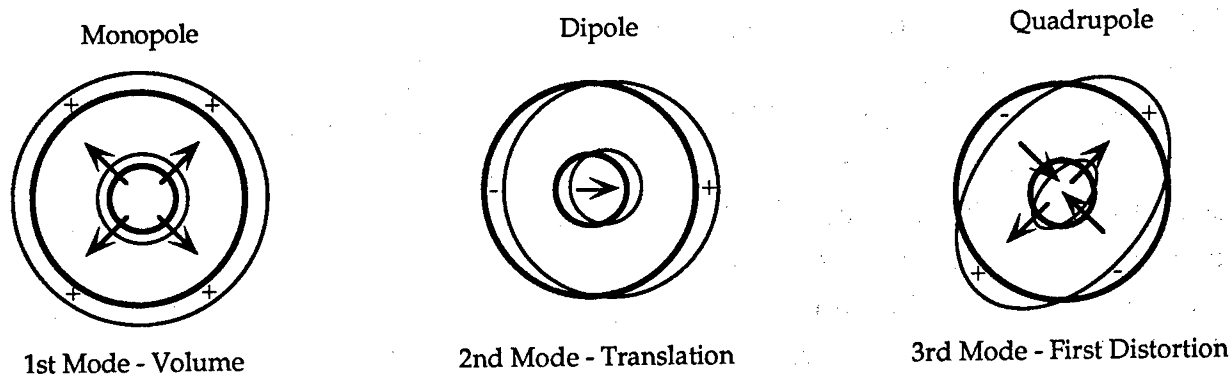

Figure II.1
Sound Sources

Next in complexity is the dipole generated by a sphere vibrating in its *second mode,* that is, vibrating in a line about its mean position without change in its diameter. It requires a periodic force to move the surrounding fluid aside, and the resultant sound radiation is strongest in the line of motion, and zero normal

to it. Gutin and Yudin associated this force with the aerodynamic force acting on a body, or rather, the reaction to that, that is, the force acting on the medium.

In the *third mode,* the quadrupole, a vibrating sphere deforms into an ellipsoid, with no volume change and no net force applied. Lighthill showed that this quadrupole is the dominant source type in turbulent flow, in which there are no volume fluctuations and no net externally applied aerodynamic force.

In each case, the distant sound field velocity (or pressure) is proportional to the local velocity of the sphere in any direction, but it is also increasingly dependent upon frequency. Since frequency is generally proportional to velocity, this leads to the sound power radiated being dependent on the velocity at the surface of the sphere raised to the fourth, sixth and eighth powers respectively. The last is Lighthill's famous U^8 law for jet noise, where it might be imagined that turbulent eddies undergo distortions of the type indicated. A few years later, Curle's extension to Lighthill's theory produced a rigorous proof of Yudin's hypothesis for the aeolian tone, which was also used to explain the source of sound of the edge tone. A rigorous proof of Gutin's hypothesis was to follow when moving (as compared to vibrating) surfaces were incorporated.

Important extensions to Lighthill's theory followed, incorporating the effects of refraction due to the velocity gradients in the jet, and of convection at the supersonic speeds as is the case for rocket noise where a U^3 law supplants the famous U^8. All these developments, and many others, took place in the West, notably the United Kingdom, the United States, Canada, and West Germany. The Soviet literature is surprisingly silent.

Based on the notion that the pressure fluctuations in a turbulent flow must cause some compression of the fluid, and therefore generate monopole type sound, similar theories were advanced independently by Meecham and Ford and by Corcos and by Ribner in the West (1958-1959) and by Lyamshev in the Soviet Union (1961). With a deceptively simple physical appeal but plagued by mathematical complexity, this approach has not met with much favor, defying any further development. The third approach, Powell's 1964 theory of vortex sound, has been fully accepted in the West, but it has been strangely little used in the Soviet Union, even by the vortex dynamics school there. Finally, just the same

is true of the method of asymptotic expansions, several investigators being active over a period of decades, all in the West.

Thus, after the impetus of Lighthill's theory, the Western investigators, with mission-oriented support, seized and have held the leadership in this modern area of aeroacoustically generated sound, the theoretical and experimental model work being complemented by a wealth of full-scale investigations. In view of the continuing Soviet strength in the acoustics of moving media and moving sources, one has to assume that the attention of those experts was simply directed elsewhere during this long period.

While it was recognized very early that a reduction in the jet velocity (with an increased nozzle size to maintain the thrust) would be the most effective way of reducing jet noise, the cost of major engine redesign could not be justified for noise reduction alone, and many silencing devices were investigated in the 1950s and early 1960s. Most prominent were multiple nozzles and "cookie cutter" nozzles, which carried a thrust penalty which had to be tolerated. Ejectors were considered, having both noise and thrust advantages, but size, weight, and configuration problems were too great.

In the area of choked (supersonic) jet noise, where a powerful flow resonance (screech) occurs, the original work in the United Kingdom (1953) has received modest development in the West in the ensuing three decades, while work has been pursued almost continuously (at a low level) in the Soviet Union.

There is also a very noisy instability which can occur in the interaction with plane surfaces, as would occur for high-performance vertical/short takeoff and landing (VSTOL) aircraft close to the ground, clearly of great importance for shipborne VSTOL operations, although most of the work is at pressure ratios more appropriate to rockets. There has been continuing work in the Soviet Union on this problem, almost totally ignored in the West. In recent years, however, the National Aeronautics and Space Administration (NASA) has supported systematic work addressing broad-band noise as well as the discrete frequency screech, and the lead in fundamental understanding has clearly returned to the West.

The noise radiated ahead of a low bypass ratio jet engine has always been dominated by compressor noise, especially at low power settings on the ground; however, for high bypass ratios, the fan noise becomes predominant. This has received increasing attention as jet noise levels decreased, particularly due to the use of high bypass ratio engines, so that in the landing approach mode the fan became the most important noise source heard in the forward quadrant on the ground. The fan or compressor blades act as propeller blades rotating in an annular duct, with an additional source due to the aerodynamic forces caused by the interaction of one row of blades with the wakes of the preceding row, recognized very early by Soviet researchers. A judicious choice of blade characteristics can reduce the noise to an extent limited by adverse performance trade-offs.

But in this case, there is the option (at some performance penalty) of extending the intake duct (or, the exhaust duct for fan jets), and treating it acoustically. These methods are now widely applied in Western commercial aircraft. Early work concentrated on ducts with a negligible flow velocity (as in air conditioning systems), capitalized on wave-guide theory (an area of traditional Soviet strength), then on various sound-absorbing arrangements on the duct walls, and finally the effects of flow at significant Mach number were incorporated.

The other major noise source of an airplane is due to the aerodynamic flow over the airframe itself. The eddying flow due to poorly streamlined (but necessary) design features, such as fully extended wing flaps or speed brakes, or extended undercarriages, is the dominant source in the landing configuration: the noise mechanism is mainly of dipole character associated with the fluctuating aerodynamic forces. These are absent in the normal flight configuration, when the source is mainly due to the turbulence of the boundary layer as it flows over the wing or fuselage. This is analogous to the quadrupole generators of jet noise, weak compared to the dipole sources due to the fluctuating pressure on the wall of the boundary layers, if it were not for the fact that these dipole sources exactly cancel out each other when the surface is flat and large. There is, in addition, a major and usually the dominant non-propulsive aerodynamic noise source, namely, the interaction of the boundary layer with the trailing edge of a wing ("trailing edge noise"). This interaction was recognized in the late 1950s in the West, and has since been treated rather fully, but ignored in the Soviet Union. On the other hand, Soviet researchers were the first to recognize and

produce a theory in the middle 1960s for the enhanced noise radiated caused by a turbulent boundary layer flowing over suction slots, and again in the 1980s over a rough surface, although in the latter case more sophisticated Western developments were to follow very quickly.

The foregoing has tacitly assumed that the surface under the boundary layer to be rigid. In practice, of course, it is not. The rushing sound in the interior of an airplane fuselage is due to the vibrations of the fuselage skin excited by the moving pressure fluctuations of the turbulent boundary layer passing over it. This mechanism is important in certain underwater applications, for example, in the turbulent flow over a sonar dome. The common interest may have given extra stimulus to it: there is an important technical difference in that the Mach numbers in the marine application are too low to influence the mechanics of sound radiation. In any event, there has been much attention paid to this aspect in both the West and in the Soviet Union.

There is a very strong motivation to reduce the turbulent drag of an airplane for performance reasons. Much effort is being devoted in the West and in the Soviet Union to research with this objective, especially by attempting to delay the transition from laminar to turbulent flow. Success would immediately lead to reduced propulsion noise; reducing the turbulence of the boundary layer would further reduce the noise due to it. One of the inhibiting factors in achieving this delayed transition is incident noise from other sources, such as compressor or jet exhaust; so, at some point this may result in additional attention to these, especially in the aircraft configuration. Soviet researchers are well placed to consider appropriate refraction and diffraction effects in fluids with relative motion to the aircraft.

The wake of an airplane may extend a great distance behind it, particularly when the atmospheric turbulence is low. The wake has three major components, the initially very hot jet or jets, the wake caused by the resistance of the wing and fuselage, and the wing tip vortices. Eventually, these components merge with each other and finally complete dissipation occurs, although the vapor trails of high flying jet aircraft make it clear that the vortex motion may extend a very long distance behind the airplane. Except for the high velocity part of the jet close to the airplane, the actual noise produced by it is relatively small,

the wake due to friction acting like a slower inverse jet (and is therefore discussed in the section on turbulent jets). On the other hand, suitable probing of the atmosphere may disclose the earlier passage of an airplane, or perhaps even suggest some of its major features. For aircraft at modest altitudes, acoustic probing might be appropriate, in which case acoustic scattering by wake inhomogeneities, especially the effect of the vortices, would be of interest. Soviet researchers have the background to consider the basic mechanism, as much attention has been given to vortex dynamics and vortex acoustics as well as the more conventional scattering. This is considered under the heading "Vortex Acoustics" (Section II.C.3).

The following discussion considers the various aspects of how acoustic emissions influence the design of Soviet aircraft. This section will be divided into discussion of: (i) exterior noise radiation and community noise considerations of both subsonic and supersonic aircraft, (ii) cabin or cockpit interior noise and sonic fatigue, and (iii) the sonic boom problem and related supersonic steady flow aerodynamics for supersonic aircraft. There are separate concerns for military aircraft and for commercial aircraft which are discussed briefly. In the Soviet Union, as elsewhere, most of the acoustic technology development was motivated by the requirements to certify commercial transport aircraft for noise emission limits near airports, which began in 1969 in the United States. The experience of the Western nations has shown that the ability to predict and suppress noise emissions for military aircraft derives almost entirely from the commercial aircraft noise technology.

In order to appreciate where the Soviet Union is with respect to aircraft and community noise considerations, it is necessary to briefly review how acoustics has influenced aircraft designs in the West. The following is a brief account.

The noise-emission limits (as imposed by the appropriate civil aviation authority) for takeoff and landing at airports apply to both subsonic and supersonic transport (SST) aircraft. In the case of an SST, the general aerodynamic considerations demand a "slender body" configuration to minimize wave drag in supersonic flight. Along with this, comes the need for a high thrust per unit of frontal area. This translates into a requirement for a very high jet exhaust velocity. From the pioneering work of Lighthill in the United Kingdom in the

early 1950s, it is well known that a high jet velocity leads to excessive jet noise. This was borne out by the experience of the early subsonic jet transports, such as the Boeing 707, and the McDonnell-Douglas DC-8. The Boeing 707 was derived from a military aircraft (the KC-135) and no consideration had been given to noise in the design of those early military engines. Thus, it can be expected that the design of an SST to achieve low acoustic emissions and good fuel efficiency will always be a difficult task.

The second generation of subsonic commercial aircraft was introduced in the late 1960s and early 1970s, including the "widebody" aircraft, such as the Boeing B-747, the McDonnell-Douglas DC-10, the Lockheed L-1011, and the European A-300 Airbus. All of these aircraft employed fuel-efficient, high-bypass turbofan engines, which were characterized by low jet exhaust velocities. In this manner, the jet noise problem was eliminated. "Fan noise" became a controlling factor; however, because this noise is generated within the engine, it can be attenuated by acoustically absorbing liners installed in the engine inlet and exhaust ducts.

Regarding airport community noise, in the United States, the early vintage jet aircraft, certified for "airworthiness" prior to 1969, were called "Stage 1 aircraft," and were exempted from the initial federal requirements; however "Stage 1 aircraft" were prohibited from making any design changes which would increase the noise levels. Those aircraft certified after 1 December 1969 (called "Stage 2 aircraft" were required to meet Federal Aviation Regulation (FAR) Part 36, which set limits on the acoustic emissions. These limits varied with the aircraft takeoff gross weight (TOGW). The International Civil Aviation Organization (ICAO)-Annex 16 is generally similar to FAR Part 36 which will be described briefly.

FAR Part 36 defined maximum values of the effective perceived noise level (EPNL, expressed in EPNdB) in three locations: (i) for takeoff at a point beneath the flight path (extended runway centerline) at a distance of 21,325 feet (6500 meters) from the beginning of the takeoff roll; (ii) for landing approach at a distance of 6562 feet (2000 meters) along the extended runway centerline; and (iii) for the sideline at a point on a line parallel to and 1476 feet (450 meters) from the extended centerline of the runway, where the noise level after liftoff is greatest; except that for an airplane having more than three engines, this distance is 0.35

nautical miles for showing compliance with Stage 1 or Stage 2. "Stage 1" referred to limits for acoustical changes to aircraft governed under the initial law (including aircraft certified before 1969). "Stage 2" referred to aircraft certified after 1 December 1969, but prior to 5 November 1975, at which time "Stage 3" of FAR Part 36, became effective, and reduced the allowable noise levels compared to the earlier laws.

"Stage 2" noise regulations would be applicable for most of the Soviet research done during the time frame covered by this assessment. The initial "Stage 2" requirements allowed a maximum of 108 EPNdB for aircraft with TOGW exceeding 600,000 pounds for each of the three certification points, with separate schedules for reducing the allowable noise with decreasing TOGW. For the takeoff point, each halving of the TOGW requires a reduction of 5 EPNdB, down to 98 EPNdB. For the sideline and approach points, each halving of the TOGW requires a 2 EPNdB reduction below 600,000 pounds down to a maximum of 102 EPNdB for aircraft of 75,000 pounds or less.

During the early 1960s in the United States and elsewhere, supersonic transport aircraft were designed with all-supersonic missions in mind, for obvious economic reasons. It was initially assumed that there was a level of sonic boom overpressure which would be acceptable to the general public, after they had become familiar with it. A considerable effort in the United Kingdom and the United States was expended to define SST aircraft designs with efficient aircraft performance and minimum sonic boom signature.

The effort to incorporate the sonic boom signature aspects into aircraft design has a very strong interaction in the design process, since the distributions of both the lift and the cross-sectional area of the aircraft affect the lift, the drag, and the sonic boom signature. Furthermore, these considerations influenced the selection of the initial climb-out profile, since the altitude at which the Mach number first exceeded one affected the fuel consumption during the initial climb. In the late 1960s, the US Environmental Protection Agency and the Federal Aviation Administration, in response to much public protest and the prospect of massive sonic boom-related litigation, ruled that any SST would be required to fly subsonically overland. Currently the Concorde is the only operational SST, and it must abide by these rules.

For commercial aircraft, the principal concern is meeting the airport noise certification standards of the ICAO-Annex 16. This is of primary importance to permit Soviet airliners and cargo planes to land at foreign airports. This is an essential element in the Soviet economy, since they need foreign currency to purchase goods not domestically produced. Therefore, trade with the Western nations and Japan, and commercial air transport are of key importance. Thus, acoustics (considering the impacts on sonic fatigue of the structure, cabin interior noise and community noise) join the other technologies (mainly, aerodynamic, propulsion and structural design considerations) playing a role in the design "trade-off" studies. Cabin noise is not governed by federal regulations; however, the commercial airlines purchasing the aircraft set stringent "guarantee" requirements for cabin noise levels. For example, British Airways requires a guarantee on three different noise measures for every seat on the airplane.

The international regulatory environment described above is the one governing any Soviet commercial aircraft intended to fly to foreign countries, and the Soviet Union has given some consideration to the problem in connection with the supersonic transport aircraft (STA) Tu-144. Soviet researchers also considered the noise reduction aspects of advanced STA designs.

The Soviet Union, evidently for propaganda value, actually "rolled out" the Tu-144 earlier than the Concorde, and also commenced service earlier (although only on a mail run to Mongolia). Subsequently, the Tu-144 suffered several disasters, starting with a spectacular crash at the Paris Air show in September of 1983. In early 1988, the Soviet Union announced the discontinuation of Tu-144 operations (on the grounds of poor fuel economy), and later in 1988, a second Tu-144 crashed in flight tests.

The Tu-144 STA is a good example of a commercial aircraft serving as a flight test research aircraft paving the way for military aircraft (usually, the process works in reverse where the military aircraft precedes its commercial counterpart). The Tu-144 had many problems as has already been discussed. It is clear, however, that Soviet researchers used their experience on the Tu-144 as an aid to the design of their new "Backfire" and Blackjack" bombers.

As mentioned before, for the Soviet Union as elsewhere, most of the acoustic technology available was motivated by the requirements for commercial aircraft, and this knowledge is applicable also to military aircraft. Described here is the perspective of Western military aircraft designers—believed to be the same as that of their Soviet counterparts. There are several problems. First, with regard to community noise problems, military aircraft operate from their own bases, and they are exempt from FAR 36 in the United States, although military designers in the United States today are required to provide community noise metrics data for "environmental impact statements," since the government has encountered some noise-related lawsuits from the communities near military air bases. Generally speaking, however, the military is extremely reluctant to trade off any significant percentage of the performance of an aircraft for acoustics, unless the aircraft is deemed to be one possessing low observable signatures, wherein acoustic detection poses a "threat."

The problem of sonic fatigue of the aircraft structure is often more severe on military aircraft, since they utilize, for example, jet engines with very high velocities in the nozzle exhaust flows, often in close proximity to the aircraft structure. This makes acoustics a more important part of the structural design effort.

C. DISCUSSION OF SOVIET RESEARCH

The basic research topics pertinent to the subject areas have a substantial degree of commonality and it is therefore convenient to discuss them in terms of the fundamentals involved. The status of each area is given at the end of each section. The areas are:

- moving sources and moving media;
- theory of aerodynamically generated sound;
- vortex acoustics;
- transition radiation;
- shock-wave interactions;
- noise of turbulent jets;
- noise of supersonic jets;
- supersonic jet screech;
- supersonic jet impingement;

- compressor and fan noise;
- duct acoustics;
- boundary layer noise;
- structural acoustics, interior noise, and sonic fatigue of subsonic and supersonic aircraft;
- sonic boom; and
- exterior aircraft noise design considerations.

Since the number of Soviet publications is very small compared to that of Western publications in the same areas, and sometimes appeared rather infrequently by any particular author, it was found desirable to extend the literature search to the 1970s and 1960s in order to form a cohesive picture of the status of research.

1. Moving Sources and Moving Media

Blokhintzev's book, *Acoustics of a Nonhomogeneous Moving Medium,* was the first book on what is now termed aeroacoustics. It was published in Russian in 1946 and was very comprehensive for its day, but did not become known in the West until a translation appeared a decade later (1956), although two articles on propagation appeared in the *Journal of the Acoustical Society of America* in 1946. This was soon to be followed by Chernov's rather terse review, "The Acoustics of a Moving Medium" (1958), in which 15 of 40 references were not Soviet references. While Chernov noted that Stokes and Rayleigh discussed the effect of wind on sound propagation around the turn of the century (an effect important in jet noise theory), he attributed the very familiar picture employing Huygen's principle to the shock waves of a supersonic bullet to the Soviet Esclangon in 1929, and notes a recent (1953) French application to the supersonic boom of aircraft (one of surprisingly few mentions of that subject). However, propagation effects, per se, are beyond the scope of this chapter.

Blokhintzev devotes a chapter to point sources moving through a stationary medium. The chapter includes a section on propeller noise, referring to Gutin's pioneering work in 1936 (which Chernov states was based on Horace Lamb's dipole radiation theory) and to a 1941 book by E. A. Nepomnyaschiy. V. I. Sukhorukov and G. I. Sukhorukov (1986) applied such methods to the Doppler

effect when both source and receiver are moving in an arbitrary fashion. Mentioning the noise control problem of conventional and vertical takeoff (VTO) aircraft, Grigor'yev et al. (1975) considered the effect of point acoustic sources moving with a variable acceleration, using electrodynamic methods. Krasil'nikov and Pavlov (1981) used related methods to discuss point sources moving at subsonic velocities, alluding to laser induced sound, but making no reference to rather similar Western research applied to aeroacoustics problems of a decade before.

In many aeroacoustical situations, the finite size of moving sources must be taken into account, as it was in Lighthill's introduction of the important effects of convection. This was taken into account by Il'ichev and Khoka (1986) along with nonuniform motion, but with no mention of aerodynamic noise.

Diffraction and sound generation by moving plates were discussed by Krasil'shchikova (1972, 1973). The effect of reflecting surfaces in the neighborhood of moving sources has been considered, this time specifically in the airplane application; it was found that the noise spectra become distorted (Generalov and Zaguzov, 1983).

The effect of a shear flow must be considered for sources in a boundary layer (as for the wind over the ground), or in the aerodynamic flow over a surface. Referring to the former case, there are recent investigations by Lyamshev (1982), Goncharev (1984) and Ostashev (1985), and to the latter, by Marshov (1983) and Zobnin et al. (1987), as discussed in Section II.C.12 concerning boundary layer noise.

Sound transmission across the idealized surface of discontinuity between a stationary and a moving fluid has been studied several times in the West and in the Soviet Union: it was treated again by Kikina and Sannikov (1972) of the Crystallography Institute im. A. V. Shubnikov, who point out its relevance to the jet noise problem. Fabrikant published a paper in 1976 which showed that in a shear flow, resonant interaction (and possibly amplification) and flow instability occur when the local phase velocity coincides with the local flow velocity, "significant in the theory of supersonic jet noise [and] the excitation mechanism of certain types of acoustic generators (whistles)," but so far there appears to be no

sequel to this important paper, especially relevant to supersonic jets. This paper was soon followed by Gavrilenko and Zelekson (1977) and later by Kolykhalov (1985), but with no reference to aeronautical applications. The authors are associated with different institutes and the three analyses appear to be different, superficially at least, and there is no reference to each other. These represent an important extension of Western work of the 1950s.

Finally in this section, note is made of Ostashev's 1985 review of propagation in an inhomogeneous moving medium, with 91 references, 43 of which are Western. As with other surveys by senior scientists, familiarity with the pertinent Western literature in apparent even though it is rarely referenced elsewhere.

It is evident that the long standing Soviet strength in classical theoretical acoustics continues, and is probably comparable to that of the West. Yet one of the very interesting and challenging problems—that of addressing the fundamentals of the amplification, diffraction, and refraction of the sound from the moving eddies in a turbulent jet—escaped the attention of the Soviet researchers. In fact, Soviet literature is almost silent on the first aspect and totally silent on the other two aspects of the topic. The importance of the first effect—convective amplification—is an important part of Lighthill's original theory, but the importance of the others was not appreciated until nearly two decades later when it was addressed by several researchers. It is a strange feature of Soviet aeroacoustics research that these aspects—which one would expect to have had great appeal to Soviet theoreticians and which are important in Western explanations of jet noise characteristics—have been ignored.

2. Theory of Aerodynamically-Generated Sound

Lighthill's pioneering papers of 1952 and 1953, which treat the generation of aerodynamic noise in the absence of solid boundaries, mark the beginning of modern aeroacoustical theory. They have been followed by many substantial Western papers extending the theory as applied to free flows (such as jets) in one way or another, the most important from the present point of view being the inclusion of the amplification of the noise in the downstream direction due to convection of the noise generating eddies, of refractive effects, the extension to

supersonic eddies, together with an alternative "vortex theory" which has also been developed and applied. Significant Western papers in this area number dozens. The sole Soviet contribution to basic theory directly applicable to turbulent jets is Lyamshev's 1961 paper, and in terms of the local fluctuating pressure, is the same as Meecham and Ford's theory, and essentially the same as Corcos' and Ribner's theory, all of which were published within a period of two years. However, there has been no further development of these, which have been controversial in the West. As already stated above, there is a notable lack of Soviet contributions in jet noise theory by well qualified scientists in the areas of convection and refraction due to moving sources (although this is not so for boundary layers, two decades later).

3. Vortex Acoustics

The radiation of sound by individual idealized (line) vortices (using the vortex theory of aerodynamic noise) constitutes a specialized application of aerodynamically-generated sound theory, since the flow is relatively simple and completely definable (in contrast to the random nature of the turbulent flow of jets). It was studied in the West in the 1960s and 1970s, including the scattering of sound by trailing vortices in 1974. A series of Soviet publications started in 1980 using quite independent methods. Scattering theories were developed by Golemshtok and Fabrikant (1980), Fabrikant (1982, 1983) and by Klimov and Prozorovskiy (1987).

The sound emission by a vortex or by vortices was treated by Gryanik (1983), Kasoyev (1984) and by Lyamshev and Skvortsov (1984a-b). Kop'yev and Leont'yev considered the radiation and scattering of sound by a vortex, and the associated vortex instability (1983), the instability more generally (1985), the radiation from a vortex ring (1987) and showed (1986) the results to be the same as found by using Powell's theory of vortex sound.

At the same time, there has been a continuing interest in the classical hydrodynamics of vortex motions (for example, Boyarintsev et al., 1985; Abrashkin 1987; Goman et al., 1987); the influence of fluid turbulence on "acoustic turbulence" has also been considered (Moyseyev et al., 1977).

In all of these instances, the surrounding fluid has been considered to be stationary apart from the vortex-induced motions.

Thus, in contrast to the situation in other aspects of aerodynamically-generated sound, there is much recent interest in the fundamentals of vortex acoustics, in which there is notable original work, as well as an understanding of the Western approaches to the subject. Although the trailing vortices behind a lifting surface pose interesting questions of instability and of sound radiation, the present published literature search produced no evidence of any interest on that particular aspect.

4. Transition Radiation

Here the Soviet term (borrowed from electrodynamics) is used to refer to aeroacoustic situations where there is an inhomogeneity—such as a source of zero frequency or a simple line vortex—which only generates sound when its streamlines are distorted, for example, by being swept closely past an airfoil. Evidently, there must be relative movement between the otherwise quiescent source and the boundary or other inhomogeneity. A good example is the blade "slap" of helicopter noise when a blade passes closely over the vortex shed from the preceding blade (incidentally, the literature search produced nothing specifically on helicopter noise).

Starting in the late 1960s and 1970s, work in this area was conducted in connection with the "edge noise," that is, the scattering by a discontinuity of the nonacoustic energy of flow fields, the trailing edge of an airfoil in particular. The same principle also applies to the scattering of the hydrodynamic energy of a turbulent boundary layer as it passes over the trailing edge of an airfoil or over roughnesses of the surface over which the boundary layer flows. This work continues to the present in the West.

The sound generated by the passage of a vortex past an edge was treated by Kasoyev in 1976a (there was a parallel Western investigation in 1974), and of vortices in a boundary layer passing over roughnesses of the surface (1976b), and much later (1984) past a streamlined body (there is reference to an unavailable conference paper of 1975 by Kasoyev and Lyamshev on a closely related topic).

The sound generated by the passage of a small body through a turbulent fluid (Pavlov, 1982) and by a simple source of zero frequency passing over a rough surface (Pavlov and Sukhorukov, 1983) have been investigated.

Sound is also generated when inhomogeneities (vortices or density changes) are swept through a nozzle or duct of varying cross-sectional area. This has been rather fully investigated in the West, starting in the middle 1960s, but the only Soviet work appears to be the recent report of Stolyarov (1983).

Another variation is that of an acoustic source, this time of some given frequency, passing through a discontinuity from one stationary fluid to another (Nemtsov and Eydman, 1987).

In none of these cases was there any reference to possible applications of the basic theory to aeronautical problems, despite the apparent transparency in some cases. The most important case of "edge noise" for boundary layers has received no mention; but it must be assumed that Lyamshev was fully aware of at least the boundary layer noise applications.

5. Shock Wave Interactions

Soviet theoretical research on shock waves has a long and prominent tradition and continues to be very active.

The interaction of a sound wave with a shock wave was first considered in the West in 1946, and in more detail in the 1950s, with the experimental work employing shock tubes. Soviet work started in the 1950s (Kontorovich, 1957, 1959) and was comparable to the Western work, but with more detailed treatments being of current interest (Kuznetsov, 1986). These works indicated that the sound wave may suffer attenuation or be amplified, depending on the circumstances. Some experimental work (using a shock tube) on the same topic has been done also (Ibragim et al., 1978). These theories considered the shock wave to be a discontinuity, and a more detailed analysis taking into account real gas effects was conducted more recently by Osipov and Uvarov (1986).

Since the 1950s, the sound produced by the interaction of shock waves with vortices and other inhomogeneities (such as entropy patches) has been studied both theoretically and experimentally in the West, being considered to be an important source of noise, for example, in imperfectly expanded supersonic jets. The Soviet interest seems to be limited to the collision with a vortex ring, considered theoretically by Shugayev (1976) and experimentally by Klimov (1978).

The prime motivation of the Soviet theoreticians appears to be understanding the resultant shock wave motions (there being a voluminous literature besides the pertinent few mentioned here), rather than the sound generation as has been the case in the West.

6. Noise of Turbulent Jets

Studies of the noise generation by turbulent subsonic jets in the Soviet Union as elsewhere are based on Lighthill's theory of 1952, this theory being couched in terms, which when suitably and rather grossly approximated, are similar to those of turbulence theory and measurement. There are numerous studies in which estimates have been made of the contribution of the various terms in Lighthill's equation, some in considerable detail. However, there is surprisingly little information in the Soviet literature. Munin and Shchepochkin (1972) use a fairly simple similarity formulation based on turbulence measurements which were reported to have been made by Vlasov (1965), and apparently showed remarkably close agreement for the noise power with the noise measurements previously made by Vlasov and Munin (1965), even though convective amplification was ignored. Later work was based on Western theories of Mach-number effects and of the "intrinsic" and "shear" noise ideas to extend this to produce estimates of the directionality (Kuznetsov and Munin, 1981). It was also noted, albeit briefly, that an increase in the initial turbulence at the nozzle was observed to increase the noise by 7 dB and more detailed studies followed (Munin et al., 1983). This effect had been described in the Western literature some years before.

While it has been usual and desirable to research fundamental jet noise using jets which have low levels of noise and turbulence in the nozzle, it has been realized all along that high levels of both turbulence and noise pass from

the engine into the nozzle, and this results in an increased generation of noise by the jet itself (at low jet speeds, this is often called "excess" noise). The result is discussed by Zhvalov et al. (1980a), who provide a comparison of engine data (in a nondimensional form) and model data, and attribute the increase in noise of the former over the latter to internal sources of sound and turbulence in the nozzle.

There has also been continuing work on the noise aspects of combustion, for example, the effects of noise on combustion and the generation of noise by combustion. There has been interest in the associated question of combustion stability (Aslanov, 1971; Kondrat'yev and Sushkov, 1980), and some noise research (Kidin and Librovich, 1983), while Khristich et al. (1986) specifically consider combustor noise and its reduction. Ivanov (1970) and later Borisov and Gynkina (1975) investigate the influence of sound on the diffusion of a jet, mentioning its relevance to combustion, and Skylarov and Furletov (1983) experiment with the effects of standing acoustic waves on combustion. Noise may also be generated by the large temperature variations in the combusted jet flow passing through the nozzle, a subject treated rather thoroughly in the West, but apparently only recently addressed in the Soviet Union (Stolyarov, 1983). Research on the propagation of sound, such as from combustion through a nozzle is discussed in Section II.C.11.

The discovery of the presence of large-scale coherent structures in turbulent jets, especially when stimulated (usually acoustically), resulted in a worldwide basic research interest. The status of this was well summarized by Vlasov and Ginevskiy (1980) in a thorough review of this basic research (which included some French Olympus 593 engine data), with 48 references, 27 of which are Western references. We note in passing that these structures are mostly studied in low turbulence jets at Reynolds (R) numbers of less than 10^5, not representative of full-scale propulsive jets. If coherent structures really do hold the key to the control of turbulence (and therefore the noise produced by it), as hypothesized by some, then Soviet researchers will likely be able to capitalize on it without delay, even though they lag in the numerical modeling.

The effect of acoustic perturbations on the noise production has been studied in detail more recently (Vlasov et al. 1983, 1986), although the jet used also seems

too small to realistically portray full-scale engine effects. The effect of flight speed "...which is [one of the] problems [which] remain urgent, caused by the stiffening of the requirements for noise, is still insufficiently studied...." note Bakhtin et al. (1983) in the introduction to their report on experiments on a jet surrounded by a much larger moving airstream. Of course, the reduction in relative jet velocity results in a major decrease in jet noise in the aft quadrant, accounting for the traditional concentration on static jets. The variation with directivity angle of the forward flight correction to static jet noise is significant according to Western literature and still controversial.

Part of the reason for investigating the effect of sound on the jet turbulence (Kudryashov et al., 1984) is the hope that useful noise reductions may be brought about by influencing the large-scale turbulence in the jet. One embodiment of this is in the use of small jets surrounding a large central one, the high frequency sound of the former reducing the noise of the latter somewhat; this configuration is attractive because it also reduces the near-field noise which bears on cabin noise. This work is noteworthy because it reports the use of a full-scale engine, and a few actual noise levels are given (Zaguzov et al., 1988). In contrast, there is a wealth of readily available data in the West on the noise characteristics of full-scale jet engines.

Ejectors with various nozzle shapes to increase the mixing rate and allow a shorter ejector have been examined (Zhulev et al., 1985), although early models ran into shell resonance problems (Kolev, 1975a), overcome by structural redesign which removed unwanted discrete tones and also slightly reduced the broad-band noise (Kolev, 1975b). Small impinging jets close after the nozzle exit have been tested (Krasheninnikov et al., 1970; Mel'nikov et al., 1971), while a center body (forming a "plug" nozzle) tested with hot jets also resulted in lower noise levels (Zhvalov et al., 1980b). The conclusions follow those of the West: such "add on" devices generally produce a useful (though not large) noise reduction at a significant performance penalty, usually a few percent loss in thrust.

The appearance of the high bypass ratio engine resulted in a small flurry of Soviet work to understand the noise implications of its coaxial jets (Kuznetsov and Munin, 1978, 1982) and to provide data ostensibly for optimizing these "modern low-noise engines" (Kuzntesov et al., 1983; Samokhin, 1983). A lobed

inner nozzle is suggested to improve the propulsive efficiency, and is stated that it further reduces takeoff jet noise (Vasil'yev et al., 1984; Ageyev and Mamayev, 1984). If this works in practice, it is the rare case of an "add on" device reducing noise and improving efficiency, in this case to an already much improved situation.

There is no evidence of Soviet interest in the noise of turbulent jets from noncircular nozzles, such as elliptical or rectangular, although studies have been made of the vortex formations in the flow from rectangular nozzles at the Reynolds numbers common in such work, $R < 105$, (Ukhanova and Voytovich, 1984). Nor has there been any work reported on the shielding of one jet by another, or shielding by nearby surfaces (although as indicated in Section II.C.1 concerning moving sources, the basic mathematical tools seem to exist). Even the pertinent question of the effect of reflection from the ground of the noise of static jet engines, discussed at some length in the West, receives no mention (again, Soviet researchers are very well placed to consider arbitrary ground impedance for this problem).

One novel suggestion is that of using high intensity sound to interact nonlinearly with unwanted aerodynamic noise, resulting in its absorption, but a practical means of implementing the idea was not presented (Kolotilov and Yarov, 1975); the idea seems not to have been pursued.

A turbulent wake acts like a moving jet, with its velocity reversed, that is, similar to an inverse moving jet. Lyamshev and Skvortsov (1983) are the only ones to discuss such a flow, but the low Reynolds number and the axial symmetry are more suggestive of the wake behind a model in a wind tunnel rather than behind an air vehicle.

In short, there has been continuing research in turbulent jet noise evident in the Soviet published literature, but the level has been very low compared to the Western efforts. While the literature indicates a good understanding of the phenomenon, there is very little reference to Western published literature which generally led by a few years to a decade or more.

The Soviet published literature contains only the briefest mention of full-scale data, which is nevertheless enough to indicate that the necessary facilities exist. There is only an extremely rare mention of any of the very numerous Western papers, even in papers from the Zhukovskiy Aerohydrodynamics Institute. The same is true, to only a slightly lesser extent, for either model or full-scale jet noise reduction efforts.

7. Noise of Supersonic Jets

The noise of supersonic jets has three distinctly different components:

- The noise due to turbulent mixing in the downstream part, where the "eddies" are moving subsonically; this is considered to be like that of the subsonic jet, but has not been studied to any extent separately, and will not be discussed further here.

- A powerful discrete tone, usually called "screech" in the Western literature (sometimes "howl" in the Soviet literature), a feedback phenomenon associated with large-scale disturbances interacting with the "cell" structure of imperfectly expanded supersonic jets. This is a dominant characteristic of cold jets; it may or may not arise for hot jets, although more random large-scale disturbances still interact with the cell structure to produce broad-band noise. There is another powerful discrete tone associated with similar jets impinging on obstacles, the perpendicular flat plate being of aerospace interest in that it represents the jet of high performance VSTOL aircraft or launch vehicles close to a carrier deck or the ground. This is a feedback phenomenon also, but the sound is generated by the interaction of the jet with the plate.

- Mach wave radiation from supersonic "eddies" in the shear layer at the edge of the jet. While this has been well studied in the West, in the Soviet literature it has been little more than noted a time or two to appear close to the nozzle in some of the earlier Schlieren photographs. This will not be discussed further.

In the West, theories of noise generation by eddies moving at supersonic Mach numbers, dating from 1963, were applied to the supersonic jets of afterburning jet engines and to rockets; comparisons were made with many published noise measurement data. The published Soviet literature is surprisingly completely silent on the subject, apparently failing to attract the attention one would expect from the considerable Soviet talent on moving sources, although it is known that the intellectual challenge of sound from supersonic eddies was laid out in at least one Western paper which was translated and published in a widely available Soviet periodical.[1]

8. Supersonic Jet Screech

The first four Soviet publications on this subject appeared together over a decade after the early work in the West, describing the basic phenomenon as it occurred for a jet with exit Mach number of 2.2 (Mamin and Rimskiy-Korsakov, 1968), and providing the first analytical explanation of the large-scale instabilities of the jet itself (Sedel'nikov, 1968a-b), of the jet exhausting through an ejector (Nazarova and Sedel'nikov, 1968), and of multiple jets and of jets passing over a plane boundary (Sedel'nikov, 1968c), the latter aspects of current interest in the United States, but now using much more sophisticated methods. (Incidentally, here is a rare case of a researcher in another area contributing to an aerodynamic noise problem, since Sedel'nikov was associated with the Odessa Polytechnic Institute, which has been the home of Soviet development of gas-driven ultrasonic generators, which use small-scale but high-pressure air jets for industrial processes [Rozenberg, 1969].)

Further work on the screech mechanism followed (Shikhlinskaya, 1973; Bikart, 1975). The measurements of the velocity perturbations of the large-scale disturbances across the jet flow and their propagation velocity along the jet were made with imported (DISA) hot-wire anemometers are of particular note (Glaznev, 1973), followed also by pressure and temperature measurements (Glaznev et al., 1985, 1986). Recent interferometer experiments have been con-

1 Alan Powell, "On the Generation of Noise by Turbulent Jets," Academy of Sciences of the USSR, Nat. Inst. Sci. and Tech. Info., Aviation Engine Design Series, Theory of Engines, No. 44, November 1959 (Trans. of ASME Conf. Paper 59-AV-53, March, 1959), 1959.

ducted on imperfectly expanded jet flows, but with no mention of sound generation (Panchenko et al., 1986).

Related works are an article on the cell structure of under-expanded jets (Antsupov, 1974), and a book on the same subject by Glaznev and Suleymanov (1980). In the latter, the authors mention the "acoustic jet facility" in a room 4.5 m x 5.5 m x 15 m built in the Theoretical and Applied Mechanics Institute in Novosibirsk, a major facility in which most of the supersonic jet work has been performed.

Other investigations concern the flow field, including the consideration of the reflectivity of the end of the nozzle (Neshcheret et al., 1984) and the large-scale instabilities and turbulence by numerical simulation (Zheltukhin and Terekhova, 1987).

Experiments indicated that the effect of the supersonic jet being surrounded by a subsonic one was to inhibit the screech by impeding the acoustic feedback to the nozzle (Lyutyy and Shvets, 1972).

Experiments followed on the effect of the angle of the conical divergent nozzle (Antsupov and Pimshteyn, 1973) and on the effect of reflectors which diminished or amplified the screech depending on whether they decreased or increased the feedback to the nozzle (Antonov et al., 1973), and on the effect of humidity and of jet temperature and condensation of the jet fuel exhaust (Antonov et al., 1977). On the other hand, Zheltukhin and Terekhova (1987) investigate the large scale mixing process in the absence of screech.

Antonov et al. (1976) investigate how the jet spread is related to the amplitude of the sound at the jet nozzle, this followed by the idea of controlling screech by directing intense sound waves onto the jet. In an experimental investigation, the jet was found to respond only to the incident frequency (within limits) with a significantly increased mixing rate (Yeremin and Kondrat'yev, 1980; Glaznev and Suleymanov, 1984), but a practical means of implementation was not suggested. A noise suppressor consisting of retractable bars penetrating the jet from a central tailcone reduced the nonresonating broadband noise (there was no screech) by breaking up the cell pattern, achieving a rather modest 8-dB reduc-

tion on a hot jet model for a thrust loss of five percent (Sorkin and Tolstosheyev, 1982).

Thus, we see a continuing Soviet research program concerning various aspects of jet screech from its initiation to the present, which has not been the case in the West, although the recent high level of interest in the United States in supersonic jet noise has more than closed the gap with more sophisticated studies of the decaying jet structure, its instabilities, and the manner in which they generate noise (whether or not there is flow resonance), the latter important aspect being surprisingly absent from the Soviet work. Untypically, Soviet researchers have acknowledged Western work in this area from the beginning, and no doubt will benefit from the latest developments.

9. Supersonic Jet Impingement

Interest in supersonic jet impingement began in earnest because of heat transfer questions in the vertical launch of rockets (for example, Belov et al., 1972), and much experimental and theoretical effort has gone into understanding the basic steady flow pattern of underexpanded supersonic jets interacting with rigid surfaces perpendicular to the jet. The theoretical work has been highly analytical (for example, Poluboyarinov and Spirin 1970; Sokolov, 1978) until numerical methods were introduced, for example, the article by Sokolov and Uskov (1986) which presents 23 Soviet references and, untypically, two Western references. There is virtually no reference to considerable comparable Western work in the Soviet publications reviewed; the work appears to be quite independent.

Actually, it had been reported by Ginzburg et al. (1970) that the flow using model air jets is sometimes highly unstable, and there followed a continuing research program into the phenomenon, while there was no apparent interest in the West where it was considered to be little more than a nuisance to the heat transfer experimenters. (This makes an interesting contrast to the case of the subsonic jet, which has been treated at great length in the West, with scant interest in the Soviet Union.)

Systematic studies in a continuing experimental program were conducted mainly in the 1970s (Semiletenko et al., 1974; Golubkov et al., 1974; Ginzburg

et al., 1975a-b; Bikart and Shirayev, 1975; Glaznev, 1977). A notable and important paper from the basic research point of view is one by Glaznev et al. (1977), which traces the feedback path in the complex flow in some detail, with the support of difficult measurements of the disturbances in the flow. This work, of over a decade ago, shows a very sophisticated understanding and experimental approach, which has yet to be surpassed in the West.

All of this Soviet research has concentrated on determining the parameters which resulted in the violent resonant oscillation, and on determining the basic feedback mechanism, with no attention to the precise mechanism by which the sound is actually generated.

A variation on the impingement on a flat plate is the now classic "Hartmann resonator" in which the the jet is directed into a cavity, still not fully understood after over half a century of investigations. This and associated ultrasonic generator work (Rozenberg, 1969) has been pursued at the Odessa Polytechnic Institute (Borisov, 1969; Borisov and Gynkina, 1975), by Knysh and Lukachev (1980) at the Aviation Institute im. S. P. Korolev in Kuybyshev, then picked up by the flat plate investigators at the Theoretical and Applied Mechanics Institute in Novosibirsk (Glaznev et al., 1973), and by Kotov and Ugryumov (1983) at Leningrad State University im. A. A. Zhdanov.

More recent work has been conducted by Glaznev and Suleymanov (1984) on the mechanism by which the jet instabilities for impingement on a flat plate are excited, while a numerical (CFD) investigation of the starting process when the jet suddenly starts by Serova (1981) closely parallels similar work in the West at the same time. All this work is with cold air jets with presumably relative low initial turbulence: there are no data, or even any comments, as to how this very interesting and continuing fundamental work compares with the full-scale situation. The pressure ratios pertinent to high-performance aircraft or missile engines is at the low end for those used in most of the investigations, much of the work having pressure ratios appropriate to rocket or other jets in a rarefied atmosphere.

10. Compressor and Fan Noise

The discrete frequency noise of compressors was treated theoretically and experimentally by Bazhenov et al. (1968a) several years after the first Western work on the subject. They study the sound radiated by the rotation of the blades—as for a propeller, and that due to the interaction between rotating and fixed rows of blades. Studies of the noise due to the shedding of vortices continued after a long gap since Yudin's (1944) pioneering work in connection with propellers; Bazhenov et al. (1968b) consider the effect of roughness and grooves on the cylinders. While reduction of up to 10 dB was attained, such techniques could have little appeal to compressor designers. Later, the same authors conducted experiments on the effect of initial turbulence on the noise generation (1976), while Rimskiy-Korsakov (1976) conducted some analytical work (incidentally, with no reference to his earlier work).

Bazhenov and Rimskiy-Korsakov (1975) indicate that "it is impossible in the majority of cases to calculate the noise level generated by solid bodies...therefore...publications devoted to the noises of vane machines are primarily experimental." (They also refer to an unavailable 1958 monograph by Yudin regarding fan noise and its suppression.)

Bazhenova (1975) considers the near-field pressures of the vortex noise of a blade system; while vibration excitation would appear to be a possible motivation for this experiment, the author alludes to the "efficient spacing of objects...in zones with the least noise." As for the former motivation, we note the later works of Bazhenov et al. (1983a) in which the effect on vibration of bending the blades backwards is investigated; but this concerns centrifugal fans common to large industrial cooling systems, but no longer found in aircraft propulsion engines. On the other hand, their experimental techniques for fluctuating pressure measurement on the blades could be applied to axial compressor blades and the duct walls, and elsewhere (Bazhenova et al., 1983b-c). There is the interesting question of how the presence of a duct influences the nature of the fundamental sound source, addressed by Bazhenov and Bazhenova (1980), and considered earlier in a more general treatment by Lapin and Lysanov (1968).

While pertinent and useful, the above studies use rather modest experimental facilities. Kuznetsov and Morozov (1976) describe in unusual detail the experimental facility which they used earlier for investigating the effect of blade load on the noise of single stage axial flow compressors. Powered by a 250-kW electric motor, the compressors had a diameter of nearly a foot with realistic inlet speeds (up to 230 meters/second).

A contemporary technical review published in a Western journal by Rimskiy-Korsakov (1975), in which 17 of the 31 references are Western, certainly indicates a thorough awareness of Western work in this field, even though most of the research papers themselves seldom mention Western publications. Significant effort has been devoted to the fundamentals of noise generation by the blading of compressors, and the Soviet understanding of the essentials is likely very good. All the same, on the basis of the available Soviet literature, there appears to be a lag of several years behind the West. As usual, no full-scale Soviet work has been published.

11. Duct Acoustics

It appears that one of the first two Soviet papers on duct acoustics with attention concentrated on the gas turbine was written by Bazhenov et al. (1968), in which they present 12 Soviet (and one Western) references dating to 1938 concerning ventilation ducts. The conclusion is that a material called "Prolon" showed "great promise" with reductions of up to 15 to 20 dB, but that branch resonators were not very effective and difficult to design. The effect of the air within the duct moving at an appreciable Mach number was not mentioned in this paper but at the same time Rimskiy-Korsakov and Kolev (1968) did extend earlier Soviet work to include the effect of finite Mach number of the medium within a duct, apparently being the first to do so.

Lapin, whose doctoral dissertation was on acoustic waveguides, published a very condensed review of attenuation in waveguides in 1975. Of 93 references, 58 are Western. In a subset of 44 references concerning ducts with moving fluid in them, only three are not Western. Theory and experiment concerning ducts with absorbing walls remain of long-standing and current interest (for example,

Lapin, 1985a); however, this review will be essentially limited to those cases with flow.

After a period of little apparent activity, three analytical papers by Lapin appeared (Lapin, 1975a-c), considering the possible instability of the mean flow when the duct walls are not rigid, the sound distribution in a duct with flow, and the case when the layer of sound absorbent material is large (though in this last case without mean flow). Il'chenko and Rudenko (1977) present an analysis of the modes in a duct with walls of arbitrary impedance. In the series of papers in Rimskiy-Korsakov's 1980 collection, *Aero-Acoustics,* Pichugin considers the equations for the attenuation due to impedance walls; Il'chenko et al. (1980) and Khaletskiy and Shipov (1980) report on experimental work, the latter describing the rather large facility at the Aviation Engine Building Institute im. P. I. Baranov (Central). This was used by Bezgreshnov et al. (1980) to make measurements for intake ducts, and apparently exhaust ducts, also. Vodopyanov and Rimskiy-Korsakov (1980) considered the acoustical attenuation when the duct flow passed a constriction, using another facility. Leont'yev and Sobolev (1980) considered the important aspect of point sources within a duct, but the moving fluid case apparently has yet to be treated.

The paper by Maslova and Naumenko from the Zhukovskiy Aerohydrodynamics Institute in the 1980 Rimskiy-Korsakov series is particularly interesting. This paper is unusual because it describes an experimental facility in more detail than is customary in a Soviet paper. Moreover, the authors refer several times to the noise due to shock-wave interaction in compressors and present some of their experimental results on the model scale. This is the only reference to this phenomenon found in the available Soviet literature (as mentioned earlier, this is in contrast to many Western publications). Furthermore, the authors also refer to a paper describing the criteria for applying model work to the full scale, and to another one which apparently proves that full-scale measurements bear these out correctly. These other papers also originate from the Zhukovskiy Aerohydrodynamics Institute, but they are not presently available. Thus, there is a clear indication of research being conducted but not reported in the Soviet published literature as it would be in the West.

The literature search revealed no more recent Soviet work besides that of Lapin (1985) and Sobolev (1986) on the attenuation of sound in ducts with flow. There has been an increasing attention to the effects on propagation of the Mach number changes due to variations in the area of the duct; so far this has not been combined with absorbing walls.

The first Soviet paper in this area appears to be written by Kondrat'yev et al. (1974), indicating that the problem "has assumed special significance in connection with undesirable self-excited vibratory processes in certain systems" and extended the then only Western approach by Powell. Other Soviet methods have been independent of the later Western techniques. Supersonic nozzles were specifically mentioned by Rudenko et al. (1975) and by Karabutov and Sapozhnikov (1986), who consider the mathematically complex case when the velocity is close to the sound speed. Thus, Gladenko and Leont'yev (1985, 1987a-b) analyze propagation in a duct carrying a high Mach number flow, as does Osipov (1985). The latter, with Levin et al. (1982) and Osipov and Shirkovskiy (1984), use finite element methods to investigate the radiation from the open end of a duct, but do not tackle the "far more complex" fluid flow case, considering Western efforts at that time to be "preliminary."

Finally, mention is made of attenuation of sound in ducts by active means, which has been the subject of much effort since the introduction of computer control, both in the West and in the Soviet Union. A paper by Arzamasov et al. (1982) lists seven Soviet articles, but no Western articles. A more recent Soviet paper by Klimov et al. (1985) presents the results of wideband experiments in which two acoustic modes are suppressed by 15 to 20 dB, there being no mean flow, as is usual. The case with mean flow and discrete frequency components of sound was all too briefly reported by Ivanov (1985) of the Institute of Commercial Aeronautical Engineering in Kiev; 20 to 30 dB of attenuation were noted.

After the first lone effort, Soviet researchers were off to a slow start on duct acoustics with flow, but the pace has picked up with some very sophisticated analytical work. Investment was made in sizeable facilities (at least one at the Zhukovskiy Aerohydrodynamics Institute), and the situation now appears to be quite good. The comments about comparisons with full-scale measurements confirm the expectation that full-scale work is carried out, but not generally

reported in the Soviet published literature. Of course, this could also apply to many other areas.

12. Boundary Layer Noise

Curle's extension of Lighthill's theory, which proved Yudin's hypothesis, followed by an important modification applicable to smooth plane surfaces in 1960, provides the main—but not the only—basis of present understanding of the noise radiated by a boundary layer over a flat plate in the Soviet Union as well as in the West.

Boundary layer noise has been the subject of increasing attention in the Soviet Union. On the fundamental theoretical side we start with Lyamshev's work (1961, 1962), followed by Smol'yakov (1973a-b), Krasilnikova (accelerating flow, 1983) and finally Lyamshev and Skvortsov (1985). Naugol'nykh and Rybak (1980) develop a different theory, a "transition" theory of the interaction between vortex modes and potential ones; this original approach has not been critically compared to the Lighthill-based methods. Reutov and Rybushkina (1987) consider the radiation from turbulent bursts in the boundary layer, giving due credit to the Western work upon which they depended. Greshilov and Mironov (1983) measure the noise of flow in a pipe to obtain data they applied to flat plates, paralleling Western work.

Of course, estimates of the sound intensity depend upon a detailed knowledge of the boundary layer, and the elucidation of this has been addressed, apparently started in the Soviet Union by Kadykov (1971), whose three references are all Western. This was followed by Marshov and Smol'yakov (1974), Lyamshev et al. (1974a-b), and by Yevtushenko and Puzino (1978). Work extending into the 1980s indicates a continuing interest in the problem.[2]

A problem in the measurement of the pressures due to the passing turbulence at the wall of a boundary layer is that there is also a pressure due to the sound generated by the boundary layer itself; the amplitude of these scale differ-

2 Yefimtsov, 1983a-b, 1984; Yefimtsov and Kuznetsov, 1983; Griko et al., 1983; Reutov, 1984; Ryzhov and Terent'yev, 1984; Greshilov, 1984.

ently with speed. This problem was considered in papers by Marshov (1983) and Zobnin et al. (1987), with both including experimental data showing how the sound from an introduced source is concentrated by refraction in the boundary layer in the downstream direction and hence interferes with measurements of the pressure due to the turbulence itself. It is interesting that the corresponding jet noise problem, of much more importance and topical earlier, has not been addressed.

Relatively strong attention has been directed towards boundary walls that are not smooth, there being a fundamental change in the radiation mechanism, which becomes much more efficient. The effect of boundary layer suction slots on the radiation mechanism was investigated very early by Lyamshev (1970, 1971), and roughness or other nonuniformities have been discussed by Kasoyev (1976b), Reutov and Rybushkina (1983a-b, 1984, 1986a-b) and Rabinovich et al. (1983), mostly by differing theoretical approaches. Lyamshev followed his work up with an experimental study of the effects of suction on the boundary layer pressure fluctuations (Lyamshev, 1975; Lyamshev et al., 1975).

In the search for means of maintaining laminar flow, one of the undesirable perturbations is acoustic; the effect of incident sound on the transition process from laminar to turbulent flow is addressed by Kachanov et al. (1976), Koslov (1982), Ruban (1984), Dovgal' and Kozlov (1983), and Maslov and Semenov (1986).

Zavol'skiy worked with the boundary layer noise researchers Reutov and Rybushkina (1983a-b) on the acoustic interaction problem, while Zhigulev and Fedorov (1987) investigated the "receptivity" of the boundary layer to acoustic disturbances, while the possibility that sound could be used to control the process was investigated experimentally by Bardakhanov et al. (1987), with some encouraging results. The effect of incident sound on flow separation at the leading edge of an airfoil is studied by Kozlov (1985) and on a sphere by Buravtsev and Ziminov (1988).

These acoustical effects are but one phase of a concerted effort on boundary-layer control, sometimes by the same researchers, for example, Kachanov et al. (1976). Mechanical excitation is reported by Tumin (1983), Tumin and Fedorov

(1983, 1985), surface vibration by Gilev and Kozlov (1984), and heating by Zavol'skiy and Reutov (1987), while efforts at actual control by mechanical means are also undertaken by Pilipenko and Shapovalov (1987) and by Yefremov et al. (1987).

Soviet research in this area is comparable to that in the West, and the discovery of means of significantly reducing boundary layer turbulence would be important for low observable applications, since not only would the boundary layer noise itself be reduced with the drag, but the propulsive jets would be less powerful and therefore quieter.

The additional radiation caused by the vibration of the boundary layer wall was considered in a very general sense by Lyamshev in 1961 and 1962. More definitive papers were presented by Dolgova (1969) and by Yefimtsov and Shubin (1977); their references imply that the first Soviet investigation occurred almost a decade after the West. Mkhitarov's earlier more general work (1974, 1975) was followed by a study making specific reference to aircraft cabin noise (1981), but there appears to be no further Soviet published work on the subject.

The fact that the flow moving past the vibrating plate on the boundary layer side at a significant Mach number affects the sound radiation was discussed by Lyamshev (1968a-b), in which specific reference was made to the body of a rocket and aircraft fuselage. The response to boundary layer fluctuations was discussed by Mkhitarov (1974, 1975)—in the latter case of a plate with an aircraft-type stiffener—and by Romanov (1985), while Yevseyev et al. (1981) considered the important effect of plate inhomogeneities, and Lapin (1985) worked on a related reflection problem.

The boundary layer work described in the preceding paragraphs almost entirely concerns flat plates, these being a reasonable simplification of airplane parts, but this is naturally a poor representation for the noise of an airframe, especially in the landing configuration. This question was approached by Vlasov and Samokhin of the Zhukovskiy Aerohydrodynamics Institute in their 1977 investigations of the noise of gliders, finding that dipole-like sound dominates, that is, fluctuating aerodynamic forces overpower the quadrupole boundary layer

noise (and presumably noise due to roughness under the boundary layer would be insignificant).

It is evident that the noise generated by a turbulent boundary layer has received more attention than has that of the turbulent jet. It might be speculated that the high level of research on boundary layers, and on its control in particular, may have had an influence, as might the fact that the subject is of marine interest also (there are two papers by Lyamshev et al. [1982, 1983] which involve the injection of bubbles or polymers). The status of noise research in this area is good and clearly benefits from continuity of effort involving a "critical mass" of researchers of varying but complementary interests. However, the Western effort leads in the broad area of boundary layer noise, but positions may be comparable in the areas of the boundary layer on a nonhomogeneous surface and the influence of incident sound.

13. Structural Acoustics, Interior Noise, and Sonic Fatigue of Subsonic and Supersonic Aircraft

The primary focus of an assessment of Soviet research in "atmospheric acoustics" is mainly with the far-field noise radiation; however, the requirements for addressing cabin noise and sonic fatigue impose aircraft weight and performance penalties above and beyond what is needed to reduce the far-field emissions. Also, the acoustic treatments and/or structural modifications needed to address structural acoustics generally are of no benefit in the suppression of exterior noise; therefore, efficient means for reducing both the structural and far-field noise problems must be found. There is some degree of technological overlap between the transmission of noise into the hull of a submarine and the analogous problems for an aircraft. Only a few citations will be given, since the interaction of sound and structures is a vast subject, and worthy of an independent assessment study.

Three articles are cited as examples of the sound transmission loss provided by multilayer sidewall constructions. Avilova et al. (1982) study shells experimentally. Beshienkov et al. (1974) study three-layer structures, and Volkov and Kudisova (1968) describe an approximate procedure for multi-layer structures. Background for this type of work and relevant non-Soviet work is described in

Brekhovshikh's *Waves in Layered Media* (1960). Two articles can be described as work on "active noise control," currently a popular subject in the United States and the United Kingdom. These articles are both by Vyalyshev and Tartakovskiy (1976, 1981). In the area of sonic fatigue, we cite Kuz'menko et al. (1978). This subject and other related solid mechanics aspects deserve independent assessment; however, it is mentioned here because the sonic fatigue problem motivates much of the work on near-field noise prediction both in the Soviet Union and elsewhere.

14. Sonic Boom

The sonic boom is the signature on the ground caused by the shock waves emanating from a body in steady, supersonic flight. The flow field is steady in vehicle-fixed coordinates, but unsteady in ground-fixed coordinates. The problem was studied extensively in the 1960s in the West, in connection with the development of the Concorde, and during a NASA/Langley sponsored evaluation of SSTs designed by Lockheed and Boeing. There exists a vast literature in the non-Soviet world.[3] By contrast, Soviet researchers have published very little. The best Soviet references are papers by Chirkashenko and Yudintsev (1985) and by Zatolka et al. (1974) on the effects of nose-blunting on sonic boom parameters, and a paper on shock waves due to meteorites (Tsikulin, 1970). The total number of references is only 10, including two Soviet papers on supersonic near-flow fields, and five US and UK papers on sonic boom. The key Soviet work was performed at the Theoretical and Applied Mechanics Institute in Novosibirsk. This work exploited the wind-tunnel technique pioneering by H. W. Carlson at NASA/Langley.[4] In this method, the sonic boom signature is measured on the wall of a wind tunnel at near-field lateral distances of 10 to 20 diameters and extrapolated to the far field, using the quasi-linear theory of Whitham.[5] The

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3 See J. J. Gottleib, "Sonic Boom Research at UTIAS," *Canadian Aeronautics and Space Journal, 20,* 5(1974), 199-222; and K. Plotkin, "Review of Sonic Boom Theory," AIAA paper 89-1105, presented at AIAA 12th Aeronautics Conference, San Antonio, Texas, 10-12 April 1989.

4 H. W. Carlson, "Experimental and Analytic Research on Sonic Boom Generation at NASA," *NASA SP-147,* 1967.

5 G. B. Whitham, "The Flow Pattern of a Supersonic Projectile," *Commun. Pure Appl. Math.,* 5(1985).

paucity of published Soviet work is interesting and puzzling, perhaps suggesting that Soviet interest in the subject was attenuated by the legal exclusion of the possibility of supersonic flight overland by supersonic transport aircraft, as a result of environmental objections in the West. The sonic boom signature is definitely of value in detecting military aircraft, and Soviet researchers may have conducted classified work on the problem.

By using the Carlson technique, Soviet researchers can, in principle, calculate the sonic boom signature for arbitrary blunt bodies, by utilizing their CFD capabilities to calculate the flow field out to a lateral distance of 10 to 20 diameters, and then apply Whitham's quasi-linear technique to obtain the far-field signature, just as was done with the experimentally determined signatures, as discussed in the previous section. Soviet researchers have a significant CFD capability, despite their apparently inferior position in regard to computer hardware. The subject of Soviet capabilities in aerodynamics is deserving of an independent assessment, and therefore, beyond the scope of this assessment of atmospheric acoustics. However, a few of the papers cited by Chirkashenko and Yudinstsev are included here as a point of departure. Generally speaking, we consider the Soviet Union to be on an equal footing with the West in the field of aerodynamics, simply because its inventory of aircraft and spacecraft is as large and varied as that of the United States. Soviet researchers have an excellent academic tradition in all aspects of applied mechanics and fluid dynamics. For example, the textbook on fluid mechanics by Lifschitz and Landau (1959) is widely recognized as among the best. The two volume monograph *Statistical Fluid Mechanics* by Monin and Yaglom (1971) reminds us of the rich Soviet pioneering work on turbulence.

The references cited in connection with the sonic boom are two monographs, for which only abstracts are available in English. The first, by Grodzovskiy (1975) concerns the aerodynamics of bodies of revolution with power-law radius profiles. The second is a 1970 book by Lyubimov and Rusanov on gas flow about blunt bodies. The first book deals with optimal shapes to minimize wave drag, or heat transfer for hypersonic speeds. The latter book deals with real gas effects with more emphasis on the requirements of hypersonic flow. Both books discuss numerical aspects such as grids and the stability of Lax-Wendroff (time-stepping) methods.

In addition, several excellent and comprehensive survey papers exist. Voskresenskiy (1983) presents results and an awareness of modern CFD methods which are of a quality comparable to US work of the same era. He cites only six references, including five of his own. Chushkin and Voskresenskiy (1980) illustrate many concrete results for complicated flows, present a knowledgeable discussion of many techniques, and cite 70 references, 56 Soviet and 14 non-Soviet. Voskresenskiy (1979) presents an excellent paper on unsteady supersonic flow near the leading edge of wings at an angle of attack with detached shock waves. This is a difficult problem, because the upper and lower wing flow fields are different, and are coupled to each other via the subsonic zone behind the detached shock wave. Chushkin (1968) presents a very comprehensive survey of numerical method of characteristics techniques for three-dimensional supersonic and hypersonic flows, including real gas effects, citing 88 references, including 42 non-Soviet works. The method of characteristics can be used in principle to calculate the sonic boom on the ground as part of the flow about the body. Such techniques have been suggested in the United States by Ferri et al. (1975), but with the provision that the grid mesh must be made more sparse in the far field to keep the computing time, data-storage requirements, and the cost within reasonable bounds.

15. Exterior Aircraft Noise Design Considerations

This discussion begins with what is believed to be the most cogent Soviet paper encountered which addresses the practical trade-offs between noise reduction and aircraft performance via the effects of engine cycle selection, noise abatement operational procedures, and shielding techniques. The paper, written by Munin et al. (1980), and appearing in the Rimskiy-Korsakov monograph *Aerial Acoustics*, is cogent (in the sense of displaying an understanding of the problems), but demonstrates very little original thinking. There is a discussion of the implications and need to meet the standards of ICAO-Annex 16, as described earlier. There is a discussion comparing the Tu-144 with the Concorde, including the statement that the sum of the certification noise levels for the Tu-144 at the three certification points (take-off, sideline, and approach) is 345 to 350 EPNdB. Throughout the paper, there is only reference to the three-point EPNL sum. From the standpoint of compliance, this is a meaningless result,

since the ICAO and US rules have severe limits on how much noise can be traded or averaged among the different certification points. Curves are shown of wing size versus take-off gross thrust, showing aircraft range and noise sum values. Various ideas are "stolen" from the US Supersonic Cruise Aircraft Research studies for NASA/Langley, which were conducted by the major airframe companies—Lockheed, Boeing, and McDonnell-Douglas—along with studies of engine cycles and noise suppressor concepts by General Electric and Pratt Whitney. The authors provide a paper study of an advanced SST which would satisfy the "Stage 2" noise requirements. This paper is a Soviet counterpart to those American studies already completed. The authors did not cite a single reference other than the ICAO noise regulation! No other papers of this type were found in the Soviet literature, whereas one could easily find many in the Western literature.

There are other Soviet papers which are relevant to the exterior noise emissions near airports of either subsonic or supersonic aircraft (depending on the choice of engine cycle parameters) but could also be classified elsewhere in this assessment. For example, the paper by Bashmakov et al. (1980) in *Aerial Acoustics* addresses refraction, but derives some practical charts illustrating the influence of temperature gradients on the radiation pattern of a spherical source. Other papers were discussed earlier which provide practical empirically-derived formulations of data useful to an aeroacoustically educated aircraft designer, but not dependent upon tedious mathematical developments.

D. PROJECTIONS FOR THE FUTURE

As demonstrated in the preceding paragraphs, the Soviet status in aircraft noise research is impressive. However, the Western effort is much larger and generally more advanced and relevant. From a Western perspective, the Soviet effort suffers from an inadequate contribution on the experimental side to balance the very strong applied mathematical effort, which is apparently sometimes executed without reference to relevant aeronautical problems. There is little evidence of Soviet applied research, and still less of full-scale (or at least, large-scale) experimental work, considered essential before application. However, it seems likely that more Soviet work has been performed than could possibly be inferred from the published literature.

These are common systemic characteristics, and, therefore, the projection for the future in Soviet aircraft noise research can be characterized as "more of the same" unless some stimulus is applied. For example, if the noise due to shock-wave interactions were to become of interest to the right Soviet scientists, then extremely rapid progress could be made, especially if the Western literature presumably could be accessed. The same is true of the supersonic boom. "More of the same" implies a continuing high class effort, heavily weighted towards applied mathematics (but complemented by strong theoretical and experimental fluid mechanics), making significant progress but much of it in an apparent unfocused manner. It is natural to expect computational methods to become more prominent as supercomputers become more available (especially for duct acoustics and exterior flow field analysis).

The Soviet research aimed at turbulence control is energetic and of high quality, and is comparable to that in the West. However, after decades of research, significant turbulence reduction remains a thoroughly elusive goal, which, if achieved, could herald significant noise signature reductions applicable to low observable aircraft.

On the other hand, if the area of air vehicle noise were to be given sufficient priority to bring together the various players, then the effort could be made more effective, and given access to the extensive Western literature, then the apparent gap in knowledge could be reduced rather quickly. On the experimental side, the customarily detailed Western literature could help result in a relatively efficient program within limited resources; presumably, most Western instrumentation could be acquired (as has been often the case in the past in this area) given the modest priority necessary and the availability of hard currency.

To develop a good predictive capability, the priority would have to be high enough to establish a more applied flavor, supported by a full-scale (or sometimes relatively large-scale) program. This is the type of work undertaken by the large mission-oriented Zhukovskiy Aerohydrodynamics Institute, which unfortunately publishes very little. If such priorities were established, then the predictive capability of Soviet researchers could be brought to approach that of the West in a short time. The strategy of "catch-up" could be played very well, but

only if the priority were sufficiently high to overcome the inertia of the system. The Soviet space and submarine silencing programs illustrate that this is possible, but they also show that the initiation of such an effort may go undetected.

It appears that the Soviet Union is publishing far less than either the United States or the United Kingdom regarding any aspects of aircraft noise, including exterior noise radiation sources, community noise impact near airports, noise suppression, cabin noise, and the resulting impact on aircraft performance and economic costs. The scarcity of research on the sonic boom is startling, unless there is a large body of classified work which is unknown to us. The lack of sonic boom work may reflect an attitude of pessimism (as in the West) with respect to the prospect of designing an SST with a sonic boom level acceptable for overland flight.

If Soviet researchers are developing "low observable" aircraft, similar to the Lockheed YF117A or the Northrop B-2, and if they have made enough progress in reducing radar cross-section and IR, then one might expect a Soviet effort to reduce the threat of acoustic detection.

E. KEY SOVIET LITERATURE

The translated journal *Soviet Physics-Acoustics* is by far the most important publication in this subject area, with 88 primary and 22 secondary references. Primary references are those in the discussion; secondary references are pertinent to the subject but have generally less significance or have very significant titles but are not available. Far fewer articles, but still quite significant, have appeared in *Fluid Mechanics-Soviet Research* (15 primary), *Fluid Dynamics* (15), and the *Journal of Applied Mechanics and Technical Physics* (11).

The collections which have appeared a few years apart, in 1968 (10 primary and three secondary), 1975 (10 primary and four secondary), 1980 (11 primary and eight secondary) and 1983 (10 primary and six secondary) by A. V. Rimskiy-Korsakov of the Andreyev Acoustics Institute are of special interest in that they contain several articles describing applied research. The same is true of the few publications from the Zhukovskiy Aerohydrodynamics Institute which have become available. These collections and the Zhukovskiy Aerohydrodynamics

Institute publications are all in Russian and relatively hard to acquire; most of the references therein are unavailable. There have been occasional one-page reports, in English, of pertinent symposia (for example, Munin, 1979; Mansfel'd et al., 1982; Bogolepov, 1983) but further information is unavailable.

An important book in Russian by Munin et al., *Aerodynamic Sources of Noise,* appeared in 1981. Reference was made to 58 of the more important Western contributions (but not including any on noise from shock wave interactions). This followed a more basic monograph entitled *Hydrodynamic Sound Sources* by Minyovich et al. in 1972. However, neither of these sources has been translated.

The paper by Munin et al. (1980), from the Rimskiy-Korsakov monograph *Aerial Acoustics* contains the best discussion of aircraft design trade-off studies as impacted by community noise considerations. The paper by Samokhin (1983) is a parametric analysis of coaxial coplanar jets, and is parallel to work sponsored by NASA/Lewis in the 1970s. Bakhtin and Vlasov (1986) address the important issue of forward flight effects on both jet and shock noise combined (since some of the nozzle exit flows are supersonic). Zhvalov et al. (1980) present some data and practical formulas for predicting the static noise emissions of heated jets, with and without a "centerbody" (that is, "plug nozzles"). Two papers by Kolev (1975a-b) relate to noise suppression afforded by ejectors, the first paper dealing with discrete components, and the latter with the mechanical properties of the housing. Ejectors, or mixing tailpipes are often used to suppress the jet noise of an existing jet engine, although at the expense of considerable weight and thrust loss. Borisov et al. (1975) discuss the noise suppression benefits of ejectors in the case where the primary nozzle flow is supersonic. The selection of "optimal" lining impedance is addressed by Maslova and Naumenko (1980) and Bezgreshnov et al. (1980). The latter work is one of the most comprehensive encountered thus far. Bazhenov et al. (1983c) address the effects of grazing flow on lining impedance. Khaletskiy and Shipov (1980) study duct attenuation in the presence of flow. Vodopyanov and Rimskiy-Korsakov (1980) study the effects of local duct restrictions on duct attenuation. Vovk et al. (1978) study propagation losses in rectangular wave guides. Three articles are cited as examples of the sound transmission loss provided by multilayer sidewall constructions. Avilova et al. (1982) study shell experimentally. Beshienkov et al.

(1974) study three-layer structures, and Volkov and Kudisova (1968) describe an approximate procedure for multi-layer structures.

F. KEY SOVIET RESEARCH PERSONNEL AND FACILITIES

There are 87 publications in which the authors are stated to be affiliated with the Soviet Academy of Sciences, 60 of those being with the Andreyev Acoustics Institute, and 27 with the Zhukovskiy Aerohydrodynamics Institute. However, it is to be noted that in 97 other relevant publications, no affiliation is provided, and it is not known from other sources.

Over the period of this survey, mostly two to three decades, a few researchers have authored papers in the subject area relatively frequently: Lyamshev (20 times); Munin and Rimskiy-Korsakov (14); Reutov (12); Leont'yev and Vlasov (10), Bazhenov, Bazhenova, Glaznev, and Lapin (9); and Borisov, Kozlov, and Kuznetsov (7). But a notable characteristic of the published literature is the very large number of authors (99) who appear only twice, while 198 authors appear only once in the period of the survey.

Key Soviet aircraft noise research personnel and their affiliations are presented in Table II.1.

Table II.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AIRCRAFT NOISE
(* indicates most prominent figures)

Acoustics Institute im. N. N. Andreyev, Moscow

This major acoustics institute has addressed all aspects of the subject area and is especially strong on boundary layer noise, flow noise and vortex acoustics, and radiation theory.

D. V. Bazhenov*
L. A. Bazhenova*
I. I. Bogolepov
Yu. Ya. Borisov
B. I. Chelnokov
I. I. Dolgova
E. M. Greshilov
I. F. Kadykov
S. G. Kasoyev
P. G. Kolev
V. I. Kondrat'yev
Yu. V. Kravchenko
A. D. Lapin*
I. V. Lebedeva
L. M. Lyamshev (Deputy Director)*
V. M. Mamin
M. A. Mironov
R. A. Mkhitarov
K. A. Naugol'nykh
A. V. Popov
M. G. Puzino
L. S. Pykhov
A. V. Rimskiy-Korsakov*
E. K. Rosenfeld
L. D. Rozenberg
S. A. Rybak
S. A. Salosina
A. G. Shustikov
A. T. Skvortsov
W. G. Smolenskiy
A. L. Sushkov
V. G. Vodopyanov
G. I. Yeremin
A. V. Yevtushenko

Applied Physics Institute, Gor'kiy

This group specializes in boundary layer noise and vortex acoustics.

A. A. Andronov
D. I. Blokhintzev*
A. L. Fabrikant*
G. M. Golemshtok
A. D. Mansfel'd
M. I. Rabinovich
V. P. Reutov*
G. V. Rybushkina*
M. M. Sushchik
N. A. Zavol'skiy
A. B. Zobnin

Table II.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AIRCRAFT NOISE (cont'd.)

Theoretical and Applied Mechanics Institute, Novosibirsk

This institute appears to be the center for supersonic jet flow structure and noise, and for boundary layer control and its acoustical aspects. This institute is also active in sonic boom research.

V. F. Chirkashenko	B. K. Kozmenko
V. S. Demin	V. Ya. Levchenko
A. V. Dovgal'	V. A. Ostapenko
V. M. Gilev	A. V. Solotchin
V. N.Glaznev*	Sh. Suleymanov
A. G. Golubkov	A. M. Yakushev
Yu. S. Kachanov	Yu. N. Yudintsev
V. V. Kozlov*	N. S. Zheltukin

Applied Mathematics Institute im. M. V. Keldysh, Moscow

This group is involved in research in supersonic and computational fluid dynamics.

K. I. Babenko	M. Ya. Ivanov
P. I. Chushkin	V. V. Rusanov
S. K. Godunov	G. P. Voskresenskiy

Aerohydrodynamics Institute im. N. Ye. Zhukovskiy (Central), Moscow

This is the principal military and commercial aircraft research establishment in the Soviet Union. Most aspects of the subject area appear to be covered, with emphasis on experimental and applied research. Most of the turbulent jet noise research is conducted here. Munin and Vlasov publish the most, the former is the senior person, while the latter appears to be his protégé. Leont'yev and Kuznetsov also publish relatively frequently.

A. V. Antsupov	Ye. A. Leont'yev*
S. P. Bardakhanov	A. G. Munin*
A. V. Dovgal'	V. G. Pimshteyn
A. S. Ginevskiy	Yu. F. Potapov
A. F. Gladenko	A. I. Ruban
R. K. Karavosov	V. F. Samokhin
Yu. S. Kochanov	M. A. Shchepochkin
F. V. Kop'yev	E. V. Vlasov*
A. N. Krayko	I. V. Volkov
L. Ya. Kudisova	B. M. Yefimtsov
V. M. Kuznetsov*	E. M. Zhmulin
M. P. Lavrukhina	Yu. G. Zhulev
O. V. Lebedeva	

Table II.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AIRCRAFT NOISE (cont'd.)

Leningrad Mechanics Institute im. D. F. Ustinov, Leningrad

This group concentrates on theoretical and experimental research on supersonic jet impingement and the noise therefrom.

I. P. Ginzburg	Ye. I. Sokolov
A. I. Kotov	N. I. Spirin
A. K. Poluboyarinov	V. S. Terpigor'yev
B. G. Semiletenko	Ye. A. Ugryumov
B. N. Sobkolov	V. N. Uskov

Moscow State University im. M. V. Lomonosov, Moscow

This is part of a larger group working on nonlinear acoustics. Pertinent research concerns transition radiation, moving sources, shock wave interaction, nozzle acoustics, and jet screech. Krasil'nikov is eminent in the nonlinear acoustics field.

V. A. Burov	A. V. Sakovets
A. A. Goryunov	O. A. Sapozhnikov
M. A. Ibragim	R. E. Shikhlinskaya
A. A. Karabutov	F. V. Shugayev
A. I. Klimov	A. I. Sukhorukov
V. A. Krasil'nikov*	T. A. Tikhonova
V. A. Oborotov	K. A. Velizhanina
V. I. Pavlov	L. Zarembo
O. V. Rudenko	

Odessa Polytechnic Institute, Odessa

This institute appears to be the center for the development of ultrasonic sound generators, driven by choked jets; the researchers here have contributed to the understanding of choked jet noise (that is, in the absence of the resonant generator).

Yu. Ya. Borisov*	L. S. Pykhov
B. I. Fedorov	T. Kh. Sedel'nikov*
N. M. Ginkina	S. A. Vinogradov
L. I. Nazarova	

Table II.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— AIRCRAFT NOISE (cont'd.)

Aviation Institute im. S. P. Korolev, Kuybyshev

This group is conducting a modest amount of miscellaneous applied research relative to aircraft acoustics.

G. G. Kartashov
Yu. A. Knysh
N. D. Kuznetsov
S. V. Lukachev
A. F. Uryvskiy
S. I. Veselov

Kiev Polytechnic Institute, Kiev

This group is working on boundary layer control and combustor noise.

A. V. Fedorov
V. A. Khristich
A. M. Shevchenko
A. M. Tumin
I. M. Zherebtsov

Other Institutes

Atmospheric Optics Institute, AS USSR, Tomsk
Atmospheric Physics Institute, AS USSR, Moscow
Automation and Electrometry/Electromeasurement Institute, AS USSR, Novosibirsk
Aviation Engine Building Central Institute im. P. I. Baranov, Moscow
Aviation Institute im. A. N. Tupolev, Kazan'
Aviation Institute im. S. P. Korolev, Kuybyshev
Aviation Institute im. Sergo Ordzhonikidze, Moscow
Chemical Physics Institute, AS USSR, Moscow
Commercial Aeronautical Engineering Institute, Kiev
Crystallography Institute im. A. V. Shubnikov, AS USSR, Moscow
Derzhavnyy University, Kiev, UkSSR
Design Bureau of the Tupolev Aviation Institute
Electronic Physics and Electronics Institute, Khar'kov
Engineering Physics Institute, Moscow
Gor'kiy State University im. N. I. Lobachevskiy, Gor'kiy
High Temperature Institute, AS USSR, Moscow
Industrial Institute, Bratsk
Khar'kov State University im. A. M. Gor'kiy, Khar'kov
Leningrad State University im. A. A. Zhdanov, Leningrad
Makeyevskiy Engineering and Construction Institute
Moscow Energetics Institute

Table II.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AIRCRAFT NOISE (cont'd.)

Other Institutes (cont'd.)

Moscow Institute of Engineering and Civil Aviation
Moscow State University, *Kafedra khimii nefti i org kataliza*
Pacific Ocean Oceanology Institute, AS USSR, Vladivostok
Physical-Technical Institute, Moscow
Physical-Technical, AS UkSSR, Khar'kov
Problems of Mechanics Institute, AS USSR, Moscow
Radiophysics Scientific-Research Institute, Gor'kiy
Shipbuilding Institute, Leningrad
Strength Problems Institute, AS UkSSR, Kiev
Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation Institute (Siberian), AS USSR, Irkutsk
Tol'yattinskiy Polytechnic Institute
Ufimskiy Oil Institute
Ukrainian State Institute
Voyenno-inzhenernaya krasnoznamennaya Akademiya imeni Kuybysheva
Vsesoyuznyy nauchno-issledovatel'skiy i proyektno-konstruktorskiy ugolnyy institut

Unknown Affiliation

A. A. Abrashkin
P. S. Antkhin
A. N Antonov
S. I. Baranovskiy
A. V. Berezutskiy
A. Bezgreshnov
E. M. Bikart
S. B. Bogomolov
G. A. Cheremukhin
I. P. Chunchuzov
Ya. Eydman
V. L. Epshteyn
R. D. Filippova
V. I. Furletov
A. V. Generalov
A. A. Gilerson
L. Gutin
M. A. Il'chenko
N. N. Ivanov
S. Ivanov
K. V. Kakhovskiy
L. I. Kaminskaya
Yu. D. Khaletskiy
N. I. Kidin
N. G. Kikina
S. P. Klimov
Yu. K. Konenkov
V. M. Kontorovich
L. F. Koslov
Yu. Krasheninnikov

Table II.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AIRCRAFT NOISE (cont'd.)

Unknown Affiliation (cont'd.)

T. N. Krasilnikova	I. A. Shirkovskiy
P. N. Kubanskiy	I. S. Shlykova
S. N. Kuznetsov	I. P. Shmakov
V. B. Kuznetsov	S. E. Shubin
V. P. Kuznetsov	V. A. Sklyarov
V. E. Kvitka	Ye. I. Sokolov
V. B. Librovich	M. N. Solovyeva
G. D. Malyuzhinets	A. I. Stankevich
E. G. Maslova	Ye. P. Stolyarov
A. A. Mazanikov	M. Sushchik
B. N. Mel'nikov	M. Terekhova
I. Ya. Minyovich	N. B. Titova
A. K. Mironov	V. I. Tokarev
A. I. Morozov	M. N. Tolstosheyev
A. S. Nadvorskiy	V. Toporov
Z. N. Naumenko	V. V. Tyutekin
T. I. Nazarenko	L. N. Ukhanova
B. E. Nemstov	A. V. Uvarov
E. D. Nesterov	S. Vinogradov
A. A. Osipov	L. N. Viotovich
A. I. Osipov	V. G. Vodopyanov
V. I. Panchenko	V. N. Yevseyev
A. D. Pernik	A. B. Yezerskiy
U. S. Petrouskiy	M. Ya. Yudelovich
N. Rudenko	Ye. Ya. Yudin
L. G. Sannikov	S. Zaguzov
T. F. Savina	N. A. Zheltukhin
S. V. Shagalov	N. Zhukov
S. P. Shalayev	V. N. Zhvalov
A. Shipov	V. P. Zhvalov
V. A. Shirayev	

CHAPTER II: AIRCRAFT NOISE

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CHAPTER III
BACKGROUND ACOUSTIC NOISE

A. SUMMARY

Only a small amount of material in the Soviet literature relates to atmospheric background or ambient noise. Soviet researchers demonstrate considerable concern for noise as a health hazard. Most of the Soviet literature concerns the measurements of the loudness of noise from various manmade sources and noise control mechanisms. Additionally, Soviet researchers appear to be concerned with infrasound from natural and manmade sources, with a strong emphasis on theoretical models.

Although the literature relating to ambient noise is sparse, Soviet researchers do demonstrate the capability to measure and to model ambient noise. They have clearly demonstrated sophisticated methodologies for the design and evaluation of underwater detection systems.

B. OVERVIEW

This chapter assesses atmospheric ambient noise research in the Soviet Union and Eastern Europe. In particular, the chapter examines the Soviet capability to understand ambient noise as it relates to the design of acoustic detection systems. This assessment is based upon a survey of over one thousand titles in the published Soviet literature. The sources of the more important documents and a table of key Soviet personnel are presented at the end of this chapter (Sections III.E and III.F).

The noise floor of an acoustic detection system includes pressure fluctuations which are unrelated to targets but, nevertheless, are transduced and mixed with target signals. Part of the noise floor is a direct result of the physical presence of the sensor-flow noise, for example. Ambient noise, on the other hand, comprises pressure fluctuations which would exist at the sensor location even without the sensor. This includes noise which propagates from nearby or distant acoustic sources, and pseudo-sound resulting from atmospheric turbulence convecting past the sensors.

The two broad classes of noise are manmade noise and natural noise. Manmade noise includes industrial and transportation noise, which predominate in urban environments. In rural or remote environments, natural noise, including meteorological and biological noise, predominates.

Ambient noise can be characterized by temporal aspects (for example, spectra) and spatial aspects (for example, source distributions). The parameters used to describe the temporal characteristics of ambient noise include the pressure time history recorded at a single sensor, which can be used to determine spectrum levels and temporal coherence. In addition, ambient noise can be characterized by slow temporal variations (for example, diurnal variations). The spatial characteristics of ambient noise include the distribution of sources of noise and the resulting wave vector spectrum and spatial coherence of the noise field.

The characteristics of a particular ambient noise field depend upon whether the noise is propagating or nonpropagating. Noise which propagates many kilometers through the atmosphere is lowpass filtered by absorption mechanisms in the air. For the sources and ranges pertinent to aircraft detection, the frequency range from infrasound to mid-frequency audible sound (that is, from 0.1 Hz up to 1 kHz) is most important. The spatial coherence of the noise depends upon the particular sources and their spatial distributions, as well as upon propagation effects, such as scattering by atmospheric turbulence.

Nonpropagating ambient noise depends upon the atmospheric turbulence length scales compared with the sensor aperture and the number of sensor elements. The spectrum of this noise is related to the spatial spectrum of the turbulence.

Sources of noise include manmade sources. In urban environments, noise is largely related to transportation. For example, there is aircraft noise particularly near airports, including subsonic propeller and jet aircraft and helicopters. Owing to the annoyance they cause, sonic booms also are generally considered an important environmental noise, though they probably are rare enough to be insignificant to sensor system performance. Road vehicles (including cars and trucks with gasoline and diesel engines) and railway trains are also major noise

contributors. In addition, certain industries, such as oil drilling installations, can generate significant noise.

Natural sources of environmental noise include meteorological sources. Perhaps the most important of these is wind, which generates aerodynamic noise as it flows over terrain or through vegetation. Wind- or temperature-associated atmospheric turbulence is another important noise source, as are precipitation and thunder. Weather fronts, as well as seismic events such as earthquakes and volcanos, are other sources of infrasound, but they are either too low in frequency or too infrequent to be of concern to the sensor systems considered in this section. Similarly, large fires can generate sporadic low-frequency sound. Near the ocean, waves can generate noise. And, in remote environments, biological noises such as from birds or insects can be significant, particularly at higher frequencies.

C. DISCUSSION OF SOVIET RESEARCH IN AMBIENT NOISE

1. Significance of Noise

The Soviet Union claims to be the first country to establish "hygienic norms and principles for the restriction of noise in industry" (*Sov. Phys.-Acoust.*, 1968). In the area of noise control, the Soviet Union has a history comparable to that of the United States. In the early 1930s, there were systematic studies of municipal noise; in the post-war era, the emphasis was on noise and vibration control. In the 1950s, attention was paid to infrasound effects on humans. In the 1960s, noise and vibration control laboratories were organized in industry. In the 1970s, jet noise and sonic boom were concerns. In the 1980s, there was a continued attention to noise reduction in industry, with new developments in active noise control.

Most Soviet publications relating to ambient noise are written from the viewpoint of noise as a health hazard. Amirov and Yarullin (1983) found a lower mortality rate among lead engineering and technical staff as compared with workers of lower rank, and ascribed this result partly to the higher noise levels in the workers' environments. Petrovich (1975) considers the hazard of exposure of an operational army to noise, including infrasound and ultrasound.

Over a dozen other recent papers concern the same theme of estimating and controlling noise effects on human health.

2. Industrial Noise

Shkarinov (1987) reviews the history of the hygienic aspects of industrial noise from the beginning of the twentieth century. Yudin et al. (1985) present an overview of industrial noise sources and diagnostic procedures. Based upon years of study of the acoustic environments of highly industrialized cities in Kazakhstan, Filin et al. (1983) developed noise-level standards for public buildings. Papers concerning noise on a more detailed level are predominantly focused upon various forms of machinery noise including fans (Gusev et al., 1983), stacking machines, compressors, and pneumatic equipment (Shcherbakov, 1983), machine tools (Gondek, 1975), and power generation equipment (Grigoryan et al., 1983). The academician Igor Glebov, a national expert in electric motor and generator design, is a coauthor of many of these papers (for example, Glebov and Danilevich, 1986). A lesser number of papers concern noise in other industrial environments, such as mines (Bellad Growberg, 1973) and petroleum processing plants (Suleymanov et al., 1983).

The papers on industrial noise exhibit a blend of acoustical measurements and prediction methods. One example of sound level measurements in a metal-working shop includes the usual linear and A-weighted levels at a dozen work-stations, and also includes octave band levels from 2 Hz to 8 kHz, reflecting the Soviet Union's concern with infrasound (Brinza et al., 1983). Time-integrated metrics of industrial noise exposure have not been seen in the available Soviet literature. There is not much indication that Soviet researchers are employing intensity methods for characterizing noise sources, as has become increasingly popular in the West.

3. Transportation Noise

Traffic noise is considered a major health problem in the Soviet Union and Eastern Europe. For instance, Blecha and Rolny (1982) study the effect of traffic noise on the inhabitants of Bratislava, Czechoslovakia, considered one of the noisiest cities in Eastern Europe. The Soviet Union developed an electric pow-

ered truck (*Komsomolskaya Pravda,* 1983), which offered quiet operation as a key advantage. In Poland, an echo chamber has been built specifically for measuring noise from tires (*Promyshlenonost' Armenii,* 1983), with the stated goal of developing mathematical models for tire noise. Numerous other papers on automobile and high-rise railway engines mention noise as a design factor.

4. Noise from Natural Sources

Soviet interest in naturally occurring ambient noise appears limited to the infrasonic frequency range. In this area, Soviet researchers conform more to the general rule of emphasizing theory over experiment. Since infrasound propagates over very long ranges, discussions of infrasound are intimately tied to the mechanics of propagation. Soviet expertise in this area is world class.

The Soviet literature contains several papers on various sources of infrasound. Bychkov (1982) measures ambient pressure fluctuations at very low infrasonic frequencies (0.01 Hz and lower), and related them to atmospheric fronts. Other papers concern gravity wave generation and propagation. For example, G. S. Golitsyn, a national Soviet figure in atmospheric physics, presents a theoretical model for gravity waves generated by meteors (Golitsyn et al., 1977). Gostintsev et al. (1985) present both experimental results and theoretical models for infrasound generated by large fires. Grigor'yev and Dokuchayev (1981) present a theoretical model for infrasound from lightning discharges. Pavlov and Sukhorukov (1984) describe a model for infrasound radiation from motion of the sea surface.

With regard to atmospheric turbulence, the Soviet literature is rich with theoretical treatises, but offers relatively little experimental data. The theory of turbulence and random fields is one of the Soviet Union's strongest scientific fields. Any textbook on turbulence (for example, Hinze, 1975) will include references to A. N. Kolmogorov, a pioneer in theories of turbulence. His name is associated with some of the most fundamental turbulence parameters. Two of his students, Andrey S. Monin and Aleksandr M. Obukhov, are also commonly referenced for developing much of current atmospheric turbulence theory. V. I. Tatarskiy published basic theories for wave propagation through turbulent media (Tatarskiy, 1971). Soviet researchers also have a field station for the study

of atmospheric turbulence at Tsimlyansk in the province of Rostov. The station has operated for roughly 30 years and includes a 40-meter tower as well as radar and acoustic sounders (Tsvang, 1985). While Soviet researchers have not published applications of their expertise in atmospheric turbulence to acoustic detection, they certainly have the capability.

Finally, the Soviet Union's extensive background in underwater noise should be mentioned. L. M. Brekhovskikh, a world-renowned authority on underwater sound, discusses the general topic of underwater noise in many papers (for example, Brekhovskikh, 1978). Specific topics include underwater noise generation (Lyamshev et al., 1985), mathematical descriptions of ambient noise fields (Zakharov, 1972; Moyseyev, 1987; Dotsenko and Il'ichev, 1987), and algorithms for the prediction of ambient noise (Nazhmidinov et al., 1982). As in most other fields, the published research emphasizes theory rather than experiment. The Soviet expertise in assessing the impact of ambient noise on acoustic detection is clearly better developed for underwater sound than for atmospheric sound.

5. Analysis of Available Literature

In comparing the Soviet and Western published literature concerning ambient noise over the last five years, it would appear that Soviet researchers are publishing about an order of magnitude fewer papers. This is largely due to structural differences within the two countries. First, there appear to be many more technical journals in the West than in the Soviet Union. Second, the Western academic communities strongly encourage frequent publications. Soviet technology is presented in conferences, but the conference reports indicate only general trends of the work. There appears to be no Soviet equivalent to the conference proceedings commonly published in the United States.

As in the West, most of the Soviet interest in ambient noise is motivated by concerns for the impact of noise on people. Industrial and urban noise studies include both measurements and theoretical models. In neither the Soviet Union nor the West is there much motivation to characterize ambient noise in remote environments. Soviet researchers do appear to show a strong interest in infrasound, but this is of questionable relevance to aircraft detection systems.

There appears to be no Soviet published literature concerning ambient noise as it specifically affects atmospheric acoustic detection systems.

The available literature indicates that Soviet capabilities for atmospheric ambient noise measurement and modeling are roughly on a par with those in the West. The lack of published work on detection systems can be interpreted in two ways. Soviet researchers may be working on such systems, but perhaps are publishing only in classified literature, or not publishing at all. They also may not be currently active in this area. The published literature does suggest that Soviet researchers are fully capable of incorporating ambient noise in the design of acoustic detection systems, particularly as shown by their extensive background in underwater acoustics.

D. PROJECTIONS FOR THE FUTURE

It is clear, primarily through experience with industrial noise, that Soviet researchers possess the capability to measure parameters of noise which affect human health. The available material suggests they already have measured the gross features of ambient noise (spectrum levels) in selected urban environments. In rural or remote environments, thus far only papers dealing with infrasonic ambient noise have been found. While these demonstrated capabilities alone would not be sufficient to perform a thorough assessment of the effects of noise on sensor systems, Soviet researchers are also potentially capable of more sophisticated analyses, as exhibited by their well-developed methodologies for characterizing and modeling underwater ambient noise. It is logical to assume that in the future these methodologies will be adapted to atmospheric acoustics and to the design and evaluation of sensor systems.

E. KEY SOVIET LITERATURE

Most references on ambient noise have been found in *Soviet Physics-Acoustics* or *Atmospheric and Oceanic Physics*. A number of abstracts relating to ambient noise are from the Tenth All-Union Acoustics Conference, held in Moscow in 1983. Additionally, the survey article "Soviet Acoustics During the Last Fifty Years" (*Soviet Physics-Acoustics*, 1968) provides background information on all aspects of acoustics, including ambient noise.

F. KEY SOVIET RESEARCH PERSONNEL AND FACILITIES

Table III.1 presents key Soviet research facilities and personnel involved in ambient noise research.

Table III.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AMBIENT NOISE

Acoustics Institute im. N. N. Andreyev, AS USSR, Moscow

L. M. Brekhovskikh - underwater acoustics
L. M. Lyamshev - atmospheric acoustics
V. I. Tatarskiy - atmospheric turbulence
Kh. Nazhmidinov - underwater ambient noise
V. V. Olshevskiy - underwater ambient noise

Aerohydrodynamics Institute im. N. Ye. Zhukovskiy (Central), Moscow

A. G. Munin - aircraft noise

All-Union Scientific Research Institute of Electromachine Structures, Leningrad

I. A. Glebov - industrial noise

Atmospheric Physics Institute, AS USSR, Moscow

I. P. Chunchuzov - infrasound
G. S. Golitsyn - infrasound
S. N. Kulichko - infrasound
A. M. Obukhov - atmospheric turbulence
V. A. Pavlov - infrasound
L. R. Tsvang - atmospheric turbulence

Chemical Physics Institute, AS USSR, Moscow

Yu. A. Gostintsev - atmospheric sciences

Earth Physics Institute im. O. Yu. Shmidt, AS USSR, Moscow

Yu. A. Gostintsev - atmospheric sciences

Table III.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AMBIENT NOISE (cont'd.)

Karaganda Medical Institute, Karaganda

A. P. Filin - environmental noise

Labor Hygiene and Professional Illness Institute, USSR Academy of Medical Sciences

A. I. Levin - industrial noise
L. N. Shkarinov - industrial noise

Oceanography Institute im. P. P. Shirshov, AS USSR, Moscow, Kaliningrad, Gelendzhik, Lyublino

A. A. Moyseyev - underwater ambient noise

Physics Institute im. P. N. Lebedev, Acoustics Laboratory, AS USSR, Moscow

B. D. Tartakovskiy - aircraft noise

Radiophysics Scientific Research Institute, AS USSR, Gor'kiy

G. I. Grigor'yev - infrasound

Research Institute of Preventative Medicine, Bratislava, Czechoslovakia

Sh. Blecha - environmental noise

Steel and Alloys Institute, Moscow

V. N. Brinza - industrial noise
M. N. Podleskikh - industrial noise

Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation Institute (Siberian), AS USSR, Irkutsk

Yu. P. Lysanov - infrasound

Water Problems Institute, AS USSR , Moscow

V. S. Bychkov - infrasound

Table III.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—AMBIENT NOISE (cont'd.)

Other Facilities

Central Institute of the Maritime Fleet Institute of Water Transportation, Leningrad
Leningrad Institute of Vocational Welfare (LIOT), Leningrad
Leningrad Mechanics Institute im. D. F. Ustinov, Leningrad
Sanitary Hygiene Medical Institute, Leningrad

CHAPTER III: BACKGROUND ACOUSTIC NOISE
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CHAPTER IV
PROPAGATION

A. SUMMARY

Soviet research in atmospheric propagation has both strengths and weaknesses vis-à-vis research in the United States. The Soviet Union has more experience with the normal mode solution to the full-wave equation, as well as with theoretical treatments of refraction and scattering. This situation probably reflects the strong emphasis on mathematics in the Soviet educational system. The United States clearly has a much larger database for propagation in the audible regions, but the Soviet Union has more extensively controlled data in the important 10- to 30-Hz frequency range.

In no area does the Soviet research appear more than 10 years ahead or behind US research. The lack of Soviet experience in topographical effects could lead to air defense arrays with geometries different from what might be considered optimum in the United States. Due to Soviet expertise in real-time atmospheric sensing, one might anticipate a high density of echo sounders in the vicinity of any large air defense system employing acoustics. These echo sounders should be easy to spot by satellite, but may resemble communication dishes.

The only anomaly found in the Soviet literature is extensive research on very high intensity acoustic beams in the atmosphere. The motivation for such work (outside of the basic science) is not clear.

Early Soviet work emphasized the audio frequency range or infrasound. More recently, however, references include a series of long-range studies at intermediate frequencies (10 to 30 Hz). These experimental studies have covered a wide range of atmospheric conditions and different propagation sites. To the extent that the Soviet researchers publish their work, US researchers can also benefit from these measures. Similar measurements are scheduled for 1992 in the United States. This would put the United States 10 years behind in prediction verification. The experimental work has been found to agree with waveguide calculations.

Ground effects are most important for targets near the horizon (such as helicopters flying nap of the earth). The Soviet technology base for applications in this area is heavily dependent upon US literature. The very fact that the first Soviet paper identified was published in 1987 suggests that Soviet researchers have less experience in this area.

An understanding of turbulence is important for estimating localization errors in proposed air defense systems and choosing optimum microphone spacings. Although Soviet researchers have a long tradition of theoretical dominance in this field, they have only recently begun to compare to experiment. This could suggest that applications of their theoretical expertise are quite recent.

Soviet researchers report routine use of full-wave solutions which include diffraction. Such calculations are not yet routine in the United States. The excellent theoretical work of Soviet researchers should enable them to predict diffraction around obstacles. In practice, however, complex surfaces can give rise to unanticipated acoustic arrivals behind a barrier. It would appear that the United States is well ahead in this area. As a result, it appears unlikely that the Soviet Union could optimize receiver spacings in a large system.

B. OVERVIEW

The transformation of an acoustic signal as it propagates from source to receiver through the atmosphere is the result of a wide array of physical phenomena. These phenomena are not greatly different in the atmosphere than under water and, for that matter, are similar to the phenomena affecting electromagnetic propagation. It is the magnitude of the effects which distinguishes acoustic propagation. As an example, a 100-Hz acoustic wave in the atmosphere experiences an attenuation per unit distance 10^4 greater than the same frequency wave propagating in water. In the atmosphere, winds can change from almost zero to an appreciable fraction of the speed of sound in minutes. Such changes in the ocean would take months. Thus, although the effects are the same, the propagation medium severely restricts useful range, frequency, and, ultimately, applications.

Acoustic propagation in the atmosphere has been studied extensively since the middle 1800s. The primary motivation has been understanding the large variety of physical phenomena involved. The design of effective foghorns and, more recently, predictions of community noise around airports have been the primary justifications given for such studies. Since these applications are concerned with human response, interest has focused on the audio region (~ 70 Hz to 10 kHz) to the exclusion of lower frequencies.

Many of the phenomena which affect outdoor sound propagation require very sophisticated mathematical treatments. Scattering by atmospheric turbulence and diffraction are good examples. Soviet research in atmospheric acoustics is dominated by theoretical studies. These complex phenomena provide Soviet theoreticians with challenging real-world problems. In contrast, US research has been more concerned with phenomena more amenable to experimental study, such as attenuation. In the US literature, it is common to treat acoustic propagation by tracing rays which give rise to the possibility of shadow zones. The Soviet literature almost always employs approximate full-wave solutions which correctly fill shadow zones with scattered and diffracted waves. Other differences will be noted in the conclusions following a more detailed analysis of Soviet work in areas important to propagation.

As an acoustic wave propagates, absorption of sound by the atmosphere will reduce the amplitude as $e^{-\alpha x}$, where α is an attenuation coefficient (Np/m) and x is the path length (which is generally greater than the distance from source to receiver due to refraction). At audible frequencies and below, the quantity depends primarily upon molecular relaxation and, to a smaller extent, thermal conductivity and viscosity. In the presence of clouds, aerosols, or fog, mass exchange with the droplets can provide additional attenuation. In general, α increases with frequency raised to a power between one and two. The magnitude and frequency dependence of α are strong functions of atmospheric temperature, humidity, and pressure. At high altitudes, trace molecules such as ozone or ions could have a significant effect.

The strong frequency dependence of atmospheric absorption shifts detectable acoustic energy to increasingly lower frequencies as the source-receiver range is increased. A 1-kHz signal suffers a loss of 0.1 decibel over a 1-kilometer path and

10 decibels over 10 kilometers, while a 100-Hz signal suffers 10^{-2} decibel and 10^{-1} decibel losses over 1-kilometer and 10-kilometer path lengths, respectively. At increasingly longer ranges, frequencies of use for surveillance lie well below 70 Hz, where the database developed for noise control applications becomes sparse.

When a receiver or source is near the ground, the ground significantly alters the acoustic field. A thorough treatment of ground effects involves an accurate mathematical formulation for spherical waves incident upon a complex impedance boundary and models for the surface impedance in terms of observable properties of the surface. Due to the complex impedance of soils, the resultant field can be quite complex, including interference at specific frequencies. For a source and receiver near the surface, direct and reflected waves can cancel out all frequencies if the range is late. In this case, there is a ground shadow penetrated by a small amplitude wave.

When sound propagates more than a few hundred meters through the atmosphere, local weather begins to play a dominant role in the received levels. Refraction due to temperature and wind gradients resulting from the diurnal heat cycle and large-scale weather patterns can significantly alter received sound levels. Short-term variations in acoustic propagation can cause signals to fade and source location to become uncertain. Weather variations have historically made acoustic detection the method of last resort.

In the United States, the effect of refraction generally has been described in terms of geometrical rays. During the day, solar heating of the earth's surface gives rise to vertical temperature gradients which decrease with altitude. At night, this situation reverses. When the temperature decreases with altitude, so does the speed of sound, and sound "rays" bend upward resulting in shadow zones. These shadow zones can be quite pronounced from mid-morning to mid-afternoon on clear days. During inversion conditions (temperature increases with altitude), sound is bent downward resulting in increased levels at a receiver near the ground. Wind contributes to refraction since the wind speed vectorially adds to the speed of sound in still air, making the index of refraction dependent upon altitude and direction. The wind speed typically varies from near zero at

the surface, to higher values at greater altitudes. Downwind from a source, increased sound levels are experienced, while upwind a shadow zone develops.

The concept of rays to describe outdoor sound propagation is most applicable at high frequencies and becomes increasingly erroneous at lower frequencies. The conditions for application of geometrical acoustics are:

$$\lambda n' << n^2,$$

$$\lambda\,[\ln(A)]\,' < 1,$$

$$\text{and} \left(\frac{\lambda}{2\pi R}\right)^{1/3} < \theta,$$

where $'$ denotes spatial derivative, λ is the acoustic wavelength, n is the acoustic index of refraction, A is the acoustic amplitude, θ is the launch angle relative to the ground, and R is the range. At frequencies below 1000 Hz, diffraction and scattering cannot be ignored.

Any time sound propagates around obstacles or inhomogeneities which have sizes on the order of the acoustic wavelength, diffraction becomes an important consideration. Classic examples of this phenomena are sound propagation over hills and propagation into refractive shadow zones. Diffraction is typically most important at very low frequencies and at long ranges. For these conditions, scattering from turbulence (discussed below) is relatively weak.

Turbulence in the atmosphere gives rise to short-lived inhomogeneities with size scales ranging from a few millimeters to hundreds of meters. The strength of these turbules is not sufficient to redirect a great deal of acoustic energy, but each turbule affects the coherence of the propagating wave to a small extent. In addition, this scattered acoustic energy can fill in shadow zones caused by refraction or reflection from the earth's surface. Due to scattering, even deep in shadow zones, measured sound levels are seldom found to be less than 30 dB below what they would be in the absence of the shadow-causing mechanism. This enhanced signal level in shadow zones is most pronounced at intermediate frequencies (100 Hz to 1 kHz) and ranges (100 meters to 10 kilometers).

In addition to filling shadow zones, turbulence can destroy coherence required for source localization. Loss of phase coherence is greatest at high frequencies, which is another reason to operate acoustic air defense systems at low frequencies since the magnitude of turbulent scattering varies approximately inversely with the square of the frequency. Even at low frequencies, turbulence gives rise to uncertainties in acoustic source location.

Although topography is not as important to acoustics as it is to radar, optimum location of receivers is more difficult for an acoustic system. For radar, one simply insures line of sight. That would work for acoustic systems as well, but a major advantage of acoustic systems is the ability to look over hills and the local horizon. Diffraction over and around obstacles with a complex impedance surface, in principle, can be included in any full-wave calculation by a suitable transformation which makes the obstacle appear as an equivalent index of refraction gradient. In practice, there is no operating code in the United States for such calculations. There are approximations based upon Keller's geometrical theory of diffraction.

At low acoustic frequencies, ray tracing leads to very poor predictions of long-range sound propagation. At infrasonic wavelengths, ray tracing again becomes useful especially to predict focusing. When the effects of terrain and scattering are included, numerical solutions to the wave equation become necessary. The cost is computation time, which can be large enough to prevent real-time applications.

Full-wave acoustic solutions take a variety of forms. The most accurate is a brute-force, finite-element approach. For propagation distances greater than several meters, such algorithms take many hours of supercomputer time. In the United States, computations have involved modified ray-tracing routines, the parabolic approximation, and the fast field program (FFP). At long ranges, correcting ray-tracing routines are typically more time consuming than the other two approaches, therefore ray tracing is generally limited to cases where extensive modifications are not required (sources nearly overhead an almost neutral atmosphere or strong downward refraction). Of the remaining two approaches, the parabolic equation (PE) has the capability of including the largest number of

effects, but is the least developed. At very long ranges, the FFP has an advantage in run time, but can still consume several minutes on a minicomputer.

C. DISCUSSION OF SOVIET RESEARCH IN ATMOSPHERIC PROPAGATION

The principle phenomena which affect long-range acoustic propagation through the atmosphere are identified below:

- absorption;
- surface effects;
- refraction;
- diffraction; and
- scattering.

Soviet research in each of these areas will be discussed. Treatment of each phenomenon alone, however, is not sufficient for system design and performance predictions. Given the nature of the phenomena, combining them into a useful form presents challenges equal to those imposed by the physics of the individual processes. For this reason, a section will be devoted to numerical techniques which offer promise of including all the phenomena listed above.

Any measurement of acoustic amplitude and phase conducted outdoors will be influenced by the above phenomena to varying degrees. Accuracy of predictions can be verified only by such measurements where interaction between phenomena is inherent. Evaluation of predictions applicable to air defense must involve low frequencies and long range. Such experiments require extensive supporting data (primarily meteorological), powerful controlled sources, and large measurement sites. A separate section is devoted to Soviet experiments meeting these constraints and possible implications.

1. Absorption

The Soviet literature contains limited original work in the general area of absorption. Absorption due to molecular relaxation, thermal conduction, and absorption is typically included in propagation predictions, but such work

usually references US literature as the source for the values used (see, for example, Bochkarev et al., 1984).

The original contributions made by Soviet researchers are associated with effects not addressed in the United States. V. I. Arabadzhi (1980) examines the possibility of sound absorption due to formation and disassociation of H_2O (water) clusters. There is some evidence to suggest that H_2O clusters might indeed have an effect on the humidity dependence of N_2 vibrational relaxation times, but the data are not sufficiently accurate to draw conclusions. Arabadzhi presents no experimental data to support his hypothesis.

At very low frequencies, radiative transport between different spatial regions of a propagation wave might contribute to absorption. V. M. Gryanik (1982) examined this mechanism and found that it is only comparable in magnitude to absorption due to relaxation for frequencies well below 15 Hz. At such low frequencies, other propagation phenomena completely dominate propagation.

The role of atmospheric absorption in determining weak-shock rise times has been overlooked by Soviet scientists as late as 1982 (Bozhkov and Kolomenskiy, 1982). This would suggest that only those Soviet researchers familiar with Western literature fully appreciate the mechanisms involved.

In the presence of fog or aerosols, acoustic absorption can result from condensation and evaporation at the surface of droplets. This mechanism can result in absorption greater than that due to relaxation processes (the terms are additive). Soviet contributions to research on this topic (Rozenfel'd, 1983a-b; Buyevich and Fedotov, 1984) are similar to work reported by Chinese scientists. Even for very dense fogs, absorption due to molecular relaxation becomes dominant above a few kHz (lower frequencies for less dense fogs). As a result, absorption due to fogs is not a major factor in noise predictions and has not been pursued extensively in the United States.

The ability to operate effectively in the presence of fogs and obscurants is often cited as one advantage of acoustic surveillance systems. The Soviet results support this conclusion. It should be noted, however, that there is no experimental confirmation provided in the Soviet or US literature.

Fogs can play a secondary role in sound propagation. In the presence of fogs, temperature gradients tend to be at a minimum, and inverted turbulence is not as strong. As a result, at low frequencies, the decrease in the received sound level should be compensated by decreased variability and wind noise. This secondary effect has not been noted in the Soviet or US literature.

One other comment concerning Soviet research on this topic seems appropriate. Predictions of absorption due to molecular relaxation depend upon a knowledge of the rate at which vibrational modes of a molecule share their energy with translation. Measurements of vibrational relaxation times or energy transfer-rate constants form the fundamental basis for accurate absorption predictions. Soviet scientists actively study such processes for molecules of atmospheric interest.

2. Surface Effects

When sources or receivers are within a few wavelengths of the earth's surface, the effects of the surface can be quite large. At long ranges (one kilometer or more) of interest for aircraft detection, the source is at a small angle above the horizon (near grazing incidence). The reflected acoustic wave suffers a 180° phase shift; when direct and reflected path lengths are essentially equal in length, the two will destructively interfere. At low frequencies, the reflection coefficient is nearly one, so interference can virtually eliminate the acoustic field except for a small-amplitude surface wave.

Soviet studies of long-range sound propagation rely on Western literature to account for surface effects. The references cited by Bochkarev et al. (1984), Generalov (1987), and Otrezov and Chunchuzov (1986) are the works of US and Canadian researchers. The Soviet use of Western research results appears to follow publication in Western journals by approximately two years. It appears reasonable to assume that Soviet researchers are aware of this work only through the published literature. Their application of this research in the above mentioned cases displays a good understanding of the phenomena.

3. Refraction

At long ranges, refraction can be a dominant factor in determining the amplitude and phase of an acoustic wave. Refraction results when an acoustic ray encounters a change in the acoustic index of refraction, except in the case of normal incidence. It is simple to think of refraction in terms of Snell's Law:

$$\eta_1 \sin \theta_1 = \eta_2 \sin \theta_2,$$

where η_1 and η_2 are indices of refraction for media one and two, respectively, and θ_1 and θ_2 are the angles of incidence (measured from normal) for the incident and refracted rays. In the atmosphere, there are no distinct boundaries (except at the surface of the earth which is treated separately), but rather gradual changes in the index of refraction. As mentioned earlier, this can result in shadow zones and focusing.

The process of refraction invokes mental images of bent-ray paths. In the atmosphere, however, use of geometrical acoustics is quite risky since the conditions for applicability are seldom (if ever) satisfied. In most cases, diffraction should be dominant. Experiments performed in the United States have shown that ray acoustics predict results reasonably well at high frequencies (where the conditions for ray acoustics are met), in downward refracting atmospheres (where diffracted energy is a small part of the total), to predict focal zones for very long range (~ 100 kilometers) propagation (absolute amplitude predictions not important), and for explosives. Based upon these successes, Western researchers frequently apply geometrical acoustics even when such application is not valid.

A proper treatment of refraction must include diffraction (see Section IV.C.4). Unfortunately, the inclusion of diffraction dramatically increases the mathematical complexity. Soviet researchers have traditionally been strong in mathematical physics, so it is not surprising that their papers on sound propagation in a stratified atmosphere and in the presence of wind incorporate the effects of diffraction.

V. Ye. Ostashev of the Atmospheric Physics Institute in Moscow published a series of papers which typify Soviet theoretical strength in predicting refractive

effects. The first paper in this series treats propagation in a stratified moving atmosphere, including effects of diffraction (Ostashev, 1984a). The solution takes the form of wave-guide/anti-wave-guide propagation. The limiting case of geometrical ray acoustics is shown to fall out naturally in the limit of high frequency. Later work extended the solution for a linear profile in the mean-flow velocity and for shadow zones (Ostashev, 1986a-b). I. P. Chunchuzov (1984) and V. P. Goncharov (1984), also of the Atmospheric Physics Institute, have made valuable contributions to this problem. This level of effort in one institute suggests a priority interest in this problem.

Soviet research in this area has not been limited to theoretical studies. G. A. Bush, A. I. Otrezov (also of the Atmospheric Physics Institute), and various co-workers have reported an impressive series of measurements in the 10- to 30-Hz frequency range. These measurements (which will be discussed in more detail in a later section), support the theoretical predictions and confirm the importance of refraction. N. N. Bochkarev (1984), of the same institute, performs measurements at higher frequencies (125 Hz and 5 kHz) and at a shorter range (less than one kilometer); he presents the results in terms of excess attenuation due to the underlying surface, atmospheric turbulence, molecular absorption, atmospheric turbulence, and refraction. These measurements dramatically illustrate the importance of wind on the amplitude of the received acoustic level.

4. Diffraction

As mentioned in the previous section, diffraction and refraction are closely related when propagating sound through the atmosphere. In the United States, diffraction is commonly treated as a correction to predictions using geometrical acoustics. In the Soviet literature, both phenomena are treated together, and then the limiting case is used to obtain geometrical acoustics.

Mathematical treatments of acoustic propagation which include diffraction are amenable to problems in addition to refraction due to temperature gradients and wind. The Soviet literature is rich in the theory of diffraction of beams important to acoustic sounding of the atmosphere. Further, full-wave solutions which include diffraction can, with a suitable change of coordinates, treat diffrac-

tion over hills and irregular terrain. No Soviet work was found which applied to this problem.

The mathematical methods for treating sound propagation including diffraction lay the necessary groundwork for modern numerical solutions. The Fourier transform used by V. Ye. Ostashev (1984b) is similar to the technique used in the FFP, which treats the diffraction problem and introduces an atmospheric parabolic approximation. The first US paper using the parabolic equation was published in the spring of 1989, though underwater applications of this technique date back more than a decade. FFP papers have appeared in the US literature since 1984.

5. Scattering

As it relates to acoustic propagation through the atmosphere, scattering typically refers to scattering by atmospheric inhomogeneities. The effect of scattering is most pronounced in shadow zones formed by refraction or interference of direct and reflected waves near the surface. Scattering and diffraction, though small, may be the only mechanism available to transmit energy into these shadows. When this is the case, the amount of available information about source location is not clear.

In the absence of a shadow zone, turbulence results in variations in received amplitude and phase. Such variations give rise to uncertainties in locations determined acoustically. Scattering by atmospheric turbulence is most pronounced for mid-range frequencies (~ 200 Hz to 2 kHz). At lower frequencies diffraction dominates. At higher frequencies, atmospheric absorption is dominant.

Scattering from atmospheric inhomogeneities does not directly affect the average received sound levels. In the absence of refraction or ground interference, the scattered energy, though redirected, would continue to propagate; the acoustic field from a spherical source would remain, on the average, unchanged since energy scattered into the field at any point should equal that scattered out. This situation is changed when refraction or the nature of the source directs the acoustic wave. In this case, scattering removes energy from the direction it

would otherwise go, redirecting some of it into regions which would otherwise not be vibrated by the source. The energy removed from the field predicted by ray theory is typically quite small (a few decibels), while the energy transferred into shadow zones is relatively large (relative to no energy in the absence of scattering or diffraction).

Soviet researchers have dominated theoretical studies of sound propagation through inhomogeneous media. V. I. Tatarskiy's book *Wave Propagation in a Turbulent Medium* (Tatarskiy, 1967) and a book by L. A. Chernov entitled *Wave Propagation in a Medium Containing Random Inhomogeneities* (Chernov, 1965) are the standard references used throughout the world. The distribution of turbulent sizes most often assumed is named after the Soviet researcher Komologorov, while the standard scattering calculation bears the name of the Soviet researcher Rytov. With this rich tradition, it is not surprising that Soviet research in scattering due to atmospheric inhomogeneities continues to be at the forefront.

The large number of excellent theoretical Soviet papers on sound propagation through an inhomogeneous atmosphere makes a thorough review of the Soviet literature impractical. Instead, the following section discusses only a few studies of particular interest.

The early work by A. S. Monin (1962) was one of the first to treat scattering of sound by atmospheric turbulence. This work by Monin also established the Atmospheric Physics Institute as a major international center for research into atmospheric acoustics.

V. M. Babich and M. M. Popov (1981) present a theoretical treatment of scattering of concentrated sound beams. The Gaussian beams chosen for the study demonstrate the Soviet strength in the interpretation of acoustic sounding. This work is particularly interesting because the authors apply the parabolic equation to solve for the direct and scattered field. The parabolic equation approach reduces the dimensionality of the wave equation, yielding an equation similar to the Schroedinger Equation with a quadratic potential encountered in quantum mechanics. This allows researchers to apply decades of studying the

Schroedinger Equation to sound propagation. V. I. Klyatskin (1980) applies a similar approach to waves in a fluctuating parabolic wave guide.

Much Soviet research of acoustic scattering by atmospheric turbulence is apparently motivated by interest in atmospheric sounders. A paper by L. G. Shamanayeva (1983) includes a careful analysis of both US and Soviet measurements of turbulence parameters. The primary concern is resolving differences between thermal structure function (C_T) measurements made with acoustic sounders and with instruments on a fixed tower.

Although Soviet strength is in theoretical work, experimental studies have not been ignored. As mentioned earlier, Bochkarev et al. (1984) attribute some experimentally measured attenuation to turbulent scattering. These measurements were made for ranges up to 835 meters at frequencies between 125 Hz and 4000 Hz. The turbulence strength was not measured directly, and the authors resorted to attributing all absorption, which was not otherwise accounted for, to turbulence. This procedure is all too often resorted to in the United States as well. The fact that their results do not agree with theory, then, is not surprising.

6. Numerical Techniques

The prediction of sound levels and phase, including all of the phenomena discussed to this point, is a challenging task. Full-wave solutions, which can potentially include all these phenomena, are beginning to evolve in the United States based on the fast field program (FFP) or the parabolic equation (PE). As mentioned earlier, Soviet researchers have adopted both FFP- and PE-like approaches in their analytical work, but no numerical results are presented based upon these techniques.

Most numerical comparisons to data are based upon wave-guide/anti-waveguide solutions. Actually, the Fourier transform involved in the FFP results in wave-guide type behavior at large ranges, so the differences between these two approaches are mostly in language and the method of implementation. It is interesting to note that when treating turbulence, Soviet researchers do not use this approach but, instead, resort to modified rays or a PE approach.

Researchers in the United States have also been unable to incorporate turbulence into an efficient FFP-type computation.

7. Long-Range Propagation Experiments

Experimental tests of theories for atmospheric sound propagation tend to be quite expensive and time consuming. In the United States, long-range studies almost always support a specific high-priority program, for example, community noise resulting from space shuttle engine tests. In this context, recent long-range propagation studies conducted in the Soviet Union are quite intriguing as well as scientifically interesting.

The measurements of primary interest in this case were conducted by the Atmospheric Physics Institute in Moscow. The first series of measurements were reported by G. A. Bush et al. (1985). The sound source was a 9-meter long, 0.8-meter diameter tube with a 4-meter injection chamber driven by an air compressor operating from a 13-kilowat power source. The source operated at discrete frequencies, with 10 Hz and 30 Hz as the most common. The acoustic power was estimated to be 90 watts at 10 Hz and 360 watts at 30 Hz. Measurements were made to the 10-kilometer range near Zvenigorod and Tsimlyansk. Simultaneous meteorological measurements were only available at Tsimlyansk. The measurements were conducted in 1982 and 1983. These results were averaged so turbulent scattering was not of great importance. Meteorological measurements were made on towers up to 32 meters with simultaneous acoustic and radio-acoustic sounding.

These measurements agreed well with wave-guide/anti-wave-guide predictions for several different atmospheric index of refraction profiles. It was concluded that at 10 Hz, atmospheric stratification dominates the magnitude of the received field even for almost neutral stratification (Otrezov and Chuchuzov, 1986) At 30 Hz, ground impedance becomes increasingly important. The authors note a lack of experimental surface impedance investigation applicable to low frequencies. The absence of such studies has also been a problem for researchers in the United States.

In addition to the long-range propagation studies mentioned above, Soviet researchers have also performed shorter range (approximately one kilometer), higher frequency (125 Hz to 5 kHz) experiments (Bochkarev et al., 1984). These measurements are quite similar to those conducted in the United States and Canada over the past decade. This particular study did not appear to have sufficient meteorological support to allow meaningful comparison to theory.

D. PROJECTIONS FOR THE FUTURE

The extensive Soviet theoretical research, which includes simultaneous treatment of diffraction and refraction, provides the necessary basis for handling complex terrain (for example, hills and obstacles). The lack of such research in the examined Soviet literature is somewhat surprising, but could be attributed to obvious military implications. In any case, reports of research about this subject are expected in the near future. Given the Soviet propensity for normal mode-type calculations, Soviet researchers are expected to resort to a mode-conversion formulation for this problem, rather than the ray-trace or PE approaches evolving in the United States. The ability to account for terrain would enable Soviet researchers to optimize sensor locations, predict dead spots (regions of no coverage), and evaluate the potential of acoustic systems once employed in hilly or mountainous terrain.

For the development of an acoustic detection/surveillance system, the designer must know, given a source with specified characteristics, what the signal will be at the proposed receiver and what variations are to be expected. With this knowledge, the designer can determine if the available signal is within the scope of available or envisioned receivers/signal processing capability. Predictions of the received signal must include all the phenomena which affect propagation. Although Soviet researchers have demonstrated (through cited literature) the necessary knowledge of each phenomena, there is no indication that they have developed a predictive capability which simultaneously includes all. It is not clear, given the complexity of the problem, that Soviet analytical prowess will be sufficient to combine these phenomena. If the need to incorporate the various phenomena into a comprehensive package has sufficiently high priority, we should expect to see numerical results in the next two to three years.

The Soviet theoretical strength in propagation through atmospheric turbulence has not been supported by experimental measurements. The large, portable sound source available at the Atmospheric Physics Institute could be used to perform measurements, at least in the low-frequency regime. The availability of acoustic and radio-acoustic remote sensors should provide the capacity to make simultaneous meteorological measurements of turbulence surpassing any similar capability in the United States. It would appear that the only ingredient yet undetermined for such measurements is the commitment. If such measurements are reported, a level of commitment is implied. The fact that such measurements have no clear application other than remote sensing of acoustic sources would suggest a military interest.

E. KEY SOVIET LITERATURE

The significant Soviet literature on atmospheric propagation is mentioned in earlier sections. Most references were found in *Soviet Physics-Acoustics* or *Atmospheric and Oceanic Physics.*

F. KEY SOVIET RESEARCH PERSONNEL AND FACILITIES

Propagation research is more dependent upon personnel than upon facilities. Table IV.1 presents key Soviet research personnel and their institution affiliation. The organizations are presented in order of the importance of their contributions.

Table IV.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—PROPAGATION

Atmospheric Physics Institute, AS USSR, Moscow

In total, 17 scientists from this institute contributed to studies of outdoor sound propagation found in the Soviet literature reviewed (spanning approximately 10 years). This represents a major concentration of personnel, perhaps the largest group in the world.

G. A. Bush
I. P. Chunchuzov
S. W. Kulichkov
A. S. Monin
M. I. Mordukhovich
V. Ye. Ostashev
A. I. Otrezov

Acoustics Institute im. N. N. Andreyev, AS USSR, Moscow

This group conducts primarily theoretical work.

V. N. Alekseyev
V. M. Frolov
L. M. Lyamshev
K. A. Naugol'nykh

Pacific Ocean Oceanology Institute, Far Eastern Scientific Center, AS USSR, Vladivostok

The primary emphasis of this group appears to be on underwater acoustics. Some of the theory, however, is applicable to atmospheric propagation.

G. I. Babkin
V. I. Klyatskin
B. M. Shoutsov

Atmospheric Optics Institute, AS USSR, Tomsk

This group conducts both experimental and theoretical studies and is primarily concerned with turbulence.

N. N. Bockharev
N. P. Krasnenko
V. P. Maravskiy
L. G. Shamanayeva

Table IV.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—PROPAGATION (cont'd.)

Radiophysics Scientific Research Institute, AS USSR, Gor'kiy

V. Ye. Fridman
L. A. Ostrovskiy
Ye. N. Pelinovskiy

Applied Physics Institute, AS USSR, Gor'kiy

D. M. Donskoy
G. K. Ivanova
A. M. Sutin

Other Facilities

Small groups of researchers are performing credible work at the following institutes:

Oceanology Institute im. P. P. Shirshov, AS USSR, Moscow (Kaliningrad), Gelendzhik, Lyublino
Scientific Research Computing Center
Physics Institute im. P. N. Lebedev, AS USSR, Moscow
Acoustics Institute im. N. N. Andreyev, AS USSR, Moscow
Mathematics Institute im. V. A. Steklov, AS USSR, Leningrad
Polytechnic Institute
A. S. Popov State Union Scientific Research Institute
Radiophysics Scientific Research Institute, AS USSR, Gor'kiy
Experimental Meteorology Institute, Obninsk
Aerological Observatory (Central), Dolgoprudnyy

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CHAPTER V
METEOROLOGICAL REMOTE SENSING

A. SUMMARY

Meteorological remote sensing has a potential role in acoustic detection/ location. Temperature profiles, wind profiles, temperature fluctuations, and velocity fluctuations all have profound effects on sound propagation. The usefulness of an acoustic system would be enhanced if these variables were determined and if predictions of detection range as a function of azimuth, altitude, and frequency were prepared in real time. In this chapter, we examine the Soviet literature on remote meteorological sensing.

The Soviet Union has a very active program in the use of acoustic sounding (SODAR) and radio-acoustic sounding (RAS or RASS) of the atmosphere. The Atmospheric Physics Institute in Moscow has a very active program in the use of sounders for atmospheric research and for sensing of wind shears around airports. The sensing systems all employ modern real-time data processing.

Although the Soviet Union lagged the West in remote meteorological sounding in the 1970s, it appears that the Soviet Union has caught up technologically and now leads the West in the practical application of sounders for measurement and wind-shear detection. SODAR and RAS are used as practical measurement devices in the Soviet Union, while in the United States they are mainly used as research tools. The potential exists for pioneering research and application of meteorological sensing in real-time prediction of propagation conditions since scientists at the Atmospheric Physics Institute also work on the measurement and prediction of low-frequency sound (see Chapter III of this report). In fact, one scientist, V. Ye. Ostashev, has worked on both research topics.

B. OVERVIEW

The propagation of sound in the atmosphere is affected profoundly by the vertical gradients of wind speed, wind direction, and temperature, as well as by the variance of the wind speed and temperature. An ideal system for acoustic

detection and location would have the capability of determining these gradients in real time and using them to predict the useful detection ranges as a function of bearing and altitude. In this chapter, meteorological systems for remote sensing that may be applicable to the battlefield sensing problems will be examined.

The first type of system developed was that of acoustic sounding (SODAR). The first sounders were built in the 1950s. An acoustic pulse in the kilohertz range is beamed upward. The signal is scattered from temperature and velocity homogeneities in the atmosphere. In a monostatic sounder, the transmitter and the receiver are co-located so that only backscattered sound is received. In this configuration, scattering is due purely to temperature inhomogeneities. The strength of the return signal is a measure of the characteristic of the temperature fluctuation (C_T^2). The wind velocity in the direction of the beam can be measured by the Doppler shift of the scattered signal. The transit time of the acoustic pulse is used to calculate the height.

A configuration with one or more remote receivers can measure additional atmospheric parameters. These type sounders are denoted as "bistatic" sounders. Bistatic sounders can measure the characteristic of the velocity variance (C_v^2) and the three-dimensional wind velocity, in addition to measuring C_T^2.

Experimental SODAR systems have employed coherent processing to investigate the acoustic wavelength versus height, and therefore, the speed of sound and temperature variation with height. Other experimental systems have used the knowledge of the scattering strength as a function of temperature and frequency to derive temperature information. At the present time, practical temperature measurement with SODAR is not possible.

For pollution studies, facsimile displays are often used to produce qualitative pictures of atmospheric processes. Inversion layers and regions of strong turbulent mixing are clearly displayed on facsimile recorders. For acoustic studies, such qualitative information is less valuable.

The accuracy of SODAR in determining C_T^2, C_v^2, and wind-speed components in the first hundred meters of the atmosphere is comparable to that obtained by free sondes, tethered sondes, and towers.

A more recently developed sounding technique which provides accurate temperature data is the radio-acoustic sounding technique. In a RAS system, a radio transmitter and acoustic transmitter are located close to one another. The radio beam is scattered off the periodic fluctuations in dielectric constants caused by the pressure fluctuation of the acoustic wave. The wavelengths of the radio and acoustic waves are closely matched in order that strong Bragg diffraction occurs.

The radio frequency maximum return provides a measure of the acoustic wavelength and, therefore, the temperature. The Doppler shift of the signals provides information about the wind velocity. In a bistatic configuration, the RAS system can provide all the information determined by the SODAR system and can also measure the temperature as a function of height. Since the radio return is quite strong (due to the Bragg diffraction and to the focusing effect of the spherical acoustic wave front), RAS sounding can be performed to greater altitudes. The primary limit is the drift in the narrow return beam. Recent Japanese research has achieved sounding of velocity components to 23 kilometers. The useful range depends on the acoustic and radio frequency used. The lower the frequency, the greater the range and the poorer the resolution. Typical systems use centimeter to meter wavelengths.

C. DISCUSSION OF METEOROLOGICAL REMOTE SENSING

The development of the SODAR and RAS systems in the Soviet Union has followed an uneven path. Soviet scientists developed the theories of the scattering of sound by wind and temperature inhomogeneities. The leaders in the theoretical developments were all Soviet researchers—Chernov, Tatarskiy, and Karavaynikov. M. A. Kallistratova (1959) constructed an experimental apparatus for studying backscatter from turbulence.

The development of this technique as a useful meteorological tool, however, was performed in the United States and Australia. L. G. McAllister in Australia was the first person to use the real-time facsimile machine to produce useful quantitative output in 1968. Theoretical and experimental work in these early years was performed at the National Oceanic and Atmospheric Administration

(NOAA). C. G. Little, S. F. Clifford, and E. H. Brown at NOAA led the theoretical and experimental work. M. A. Fukishima in Japan also contributed to progress in the early 1970s. N. Ye. Gerasyuk et al. (1981) attribute the lack of progress in the Soviet Union to the lack of commercial models of high-power electroacoustic converters. Gerasyuk also states that at the time (1981), there were only two low-powered sounders in the Soviet Union; these were at the Atmospheric Optics Institute in Tomsk and the Radio Electronics Institute im. Yangel'ya in Khar'kov.

Gerasyuk et al. (1981) developed a high-powered transmitter which produced 120 watts at 2.2 kHz in a pulsed mode. This first modern sounder was first operated in 1978. In 1978, Sidorov and Sidko patented a bistatic sounder with improved spatial resolution (Sidorov and Sidko, 1981).

The development of the RAS systems occurred almost in parallel with the development of high-power SODAR systems. In approximately 1978, a RAS system was constructed using a 3.0-centimeter aircraft radar system (Makarova, 1981). Gladkikh et al. (1984) patented a design for a RAS system in 1970. The Atmospheric Physics Institute performed combined monostatic RAS and SODAR measurements at the Zvenigorod Research Station (Azizyan et al., 1982). With this system, they measured the temperature profiles, the profiles of C_T^2, and vertical wind components to a height of several hundred meters. The system produced comparable accuracy to stationary towers.

By 1984, SODARs were commonly used for vertical sounding of the turbulence structure function. The limitation of this application, as identified by G. V. Azizyan et al. (1984), was the need for rapid digital processing of bistatic sounding data. Azizyan describes an experimental system using an *"Elektronika DZ-28"* microcomputer to process data. This system was capable of determining wind-speed components to 1-kilometer altitudes.

The Atmospheric Physics Institute also pursues development work for the application of SODAR. A joint Atmospheric Physics Institute and Hydrometeorological Institute (Czechoslovakia) project compared the results of facsimile and quantitative studies using Soviet and Czechoslovak SODARs (Kallistratova et al., 1984).

During the same time period, bistatic SODAR soundings were used to measure the wind components and to verify meteorological theories (Kallistratova et al., 1987). Systems such as the MAL-2 sounding system have been installed at airports to sense wind shears. In this application, the Soviet Union leads the United States. The monograph *Acoustic Sounding of the Atmosphere* by Krasnenko (1986) provides a detailed description of the MAL-1 and MAL-2 acoustic sounders (see also Krasnenko and Fursov, 1987).

Complete SODAR-RAS systems which measure all the wind components, the temperature profile, the temperature structure function C_T^2, and the velocity structure function have been assembled and tested by the Atmospheric Physics Institute and the Radio Electronics Institute (Petenko and Shurygin, 1984; Babkin et al., 1984).

Theoretical developments during this time period (1980 to 1987) primarily concerned accuracy estimates of both SODAR and RAS or the limitation and/or correction of wind-refraction effects on RAS. Bovsheverov and Karyukin (1981) calculate the error in C_T^2 due to horizontal wind and demonstrate that the error was small for heights up to 1 kilometer.

V. Ye. Ostashev (1982) examines the determination of temperature using bistatic acoustic sound. His scheme depends upon the solution to the inverse problem, that is, the reconstruction of the atmosphere from measured data and from propagation information. This technique requires reconstruction of the propagation paths and is more difficult than the acoustic temperature measurement method proposed by E. H. Brown et al.[1] In addition, the later Krasnenko paper (1987) states that practical temperature measurements cannot be performed with SODAR systems.

In a later paper, Ostashev (1984) concludes that the problem is not solvable in the atmosphere with present sounding equipment, but requires acoustical inter-

1 E. H. Brown, C. G. Little, and W. M. Wright, "Echosonde Interferometer for Atmospheric Research," *J. Acoust. Soc. Am.*, *63* (1978), 694-699.

ferometry. In this paper, Ostashev references the E. H. Brown et al. article from 1978.

Theoretical limits and error estimates for bistatic SODAR have been developed in two papers by A. Ya. Bogushevich and N. P. Krasnenko (1984, 1987). The first investigates refraction effects in position determination, while the second investigates vertical shear.

RAS systems are limited by the advection of the scattering volume due to winds. Bragg reflection is highly directional so that Doppler radar aiming and receiving requirements are high. Karyukin (1982) investigates these effects theoretically. Measurements reported in this paper agree well with his theory. Calm wind sounding achieved heights of 1800 meters, while 10-meters/second winds limited the results to approximately 200 meters. Kallistratova and Kon (1983) investigate the effect of turbulence on the maximum RAS range. Improved calculations are presented by A. I. Kon (1984). Continuation of this research is presented by V. D. Belyavskaya et al. (1984). A. I. Kon and V. I. Tatarskiy (1986) develop an equation for signal power necessary as a function of source receiver and atmospheric parameters.

More popular Soviet literature available only as English abstracts emphasizes the use of SODAR and RAS to support aviation. The detection of wind shear around airports is emphasized in this literature (Alekhin et al., 1987; Orlov and Yurchak, 1985; Sidko, 1982).

The other application emphasized is that of atmospheric boundary layer research (Krasnenko, 1986; Kallistratova and Kon, 1985).

D. PROJECTIONS FOR THE FUTURE

The Atmospheric Physics Institute has a strong program in meteorological remote sensing. The current principal applications are wind-shear sensing near airports and meteorological research on the atmospheric boundary layer. The same institute has a strong program in low-frequency sound propagation in the atmosphere. V. Ye. Ostashev has worked in both fields.

The common use of micro- and minicomputers indicates that the Atmospheric Physics Institute is performing high-priority research and is well supported. Given the personnel, facilities, and governmental support, the development of a near real-time sound propagation prediction capability is possible in the near future.

E. KEY SOVIET LITERATURE

The key Soviet literature concerning meteorological remote sensing is the paper by N. Ye Gerasyuk et al. (1981), which describes the development of the high-power acoustic source for sounding. The book extract from *Acoustic Sounding in the Atmosphere* by N. P. Krasnenko (1986) and the review article, "The Use of Monostatic Sonar Sets for Measuring the Meteorological Parameters of the Boundary Layer of the Atmosphere," by Krasnenko and Fursov (1987) contains detailed description and histories of the development of SODAR. The excerpt from *Radioacoustic Sounding in the Atmosphere* by M. A. Kallistratova and A. I. Kon (1985) contains similar information on the RAS systems.

F. KEY SOVIET RESEARCH PERSONNEL AND FACILITIES

A listing of key Soviet research personnel and facilities involved in meteorological remote sensing is provided in Table V.1.

Table V.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—METEOROLOGICAL REMOTE SENSING

(*italics* indicate leading personalities)

Atmospheric Physics Institute, AS USSR, Moscow

G. V. Azizyan*
V. B. Belyavskaya
B. M. Bovsheverov
N. Ye. Gerasyuk
M. A. Kallistratova
G. A. Karyukin
A. I. Kon
S. N. Kulichkov
Ye. Keder
T. I. Makarova
F. Ye. Martvel'
T. N. Nesterova
K. V. Neverovskiy
V. Ye. Ostashev
I. V. Petenko
Ye. A. Shurygin
V. I. Tatarskiy*
N. S. Time

Atmospheric Optics Institute, AS USSR, Tomsk

A. Yu. Bogushevich
N. P. Fursov
N. P. Krasnenko

Radio Electronics Institute im. Yangel'ya, Khar'kov

S. I. Babkin
Ye. G. Proshkin
Yu. N. Ul'yanov

* These personnel are not authors on recent papers but are cited very often in the Soviet literature.

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CHAPTER VI
MICROPHONE TECHNOLOGY

A. SUMMARY

A review of the Soviet literature for information on microphones reveals little documentation compared to the voluminous amounts published on the subject in the West. Nevertheless, some important conclusions can be drawn from the available Soviet literature.

Soviet researchers have described transducer systems in their literature for at least 40 years. Also for the same length of time, US researchers have described advances in Western publications. Current Soviet literature indicates that the Soviet Union has the capability to upgrade published microphone systems to at least the current level of technology in the West.

A difficult portion of any acoustic detection system will be the acoustic transducer. It must be designed to operate in all weather conditions, where high humidity and high temperature service can be expected. Transducers may also need to survive radiation effects. These factors would suggest that typical electret condenser microphones would not be satisfactory. Also, conventional condenser microphones operating under these conditions would require an expensive dehumidifier. Based on these considerations, a piezoelectric type transducer might be expected. The Soviet literature has a substantial number of references to piezoelectric devices for industrial use, so it is reasonable to assess their basic technology and manufacturing capabilities in this area as very good. In summary, in the area of microphone systems, it is not unreasonable to expect that the Soviet Union is equal to or perhaps ahead of the Western capabilities.

B. OVERVIEW

The requirements for atmospheric acoustic transducers are different from general acoustic transducers in the following ways:

- They must have an accurate response over the frequency range of 1 Hz to about 1 kHz. This is because the absorption of pressure waves in the atmosphere increases progressively as frequencies increase, such that disturbances from moderate distances are limited to frequencies below 500 Hz. If the signals arrive from great distances, say tens of kilometers, they are limited to the infrasonic range.

- Atmospheric background signals in this range are large enough that high threshold sensitivity is not required.

- Transducers must be environmentally stable since their intended use is outdoors where wide extremes in temperature and humidity can be expected.

- They must be uniform or of known phase to be processed for signal to noise gain or bearing determination.

Potentially suitable transducers can be divided into the technology areas presented in Table VI.1.

The expected environmental conditions of wide temperature extremes, humidity, dust, and rain will restrict the application technologies. If a battlefield scenario is added, the effects of nuclear radiation should be included. These provide the following limitations on the technologies: self generating magnetic and hot wire transducers are essentially velocity transducers. At low frequencies they would have a rising response characteristic. Optoacoustic transducers are complex and may have long term stability problems. Nuclear radiation would eliminate the use of electret condenser microphones since electrets could be discharged by bombardment of radioactive particles.

These factors discussed above leave the condenser transducer and the piezoelectric transducer as the primary candidates. A short description of their characteristics for atmospheric acoustic use is given below.

Table VI.1
TRANSDUCER TECHNOLOGIES

- Piezoelectric Transducer Technology
- Condenser Transducer Technology
- Acousto-optic Transducer Technology
  - Fiber Optic Sensors
  - Interferometric Sensors
  - Other Acousto-optic Sensor
- Magnetic Transducers
  - Moving Coil Transducers
  - Variable Reluctance Transducers
  - Magnetostrictive Transducers
- Hot Wire Transducer Technology

The high impedance of the vacuum tube amplifier made possible the introduction of the condenser microphone in 1917. Its simple structure allowed designs which could cover the range from a fraction of a hertz to beyond the range of audibility. With the employment of a high frequency bridge circuit to mitigate the effects of humidity, this device became the transducer of choice for studies of atmospheric sound propagation.

Numerous carrier circuits for capacitive transducers have been developed and described in the literature in the past 50 years. The development of the technology centered around improvements made possible by new materials and semiconductor components. Notable improvements have been miniaturization and the lowering of the transducer's self noise level. In the early 1960s, low frequency capacitive transducers were widely used to record acoustic signals from the atmosphere. These were coupled to long pipes with many small sound ports to average out the response to uncorrelated wind noise and high signal frequencies.

The piezoelectric microphone generates a charge directly from pressure inputs so it can not be used with carrier excitation to give response to essentially DC signals. It can produce extended low frequency response since its high internal capacitance combined with a high impedance preamplifier can give a time constant of one minute or more. Since the charge produced is inside the piezoelectric element, it can be sealed against adverse environmental conditions.

The choice between capacitance and piezoelectric microphones depends upon the degree of interest in very low frequencies. If the reception of signals at frequencies below 0.1 Hz is required, the condenser microphone would be indicated because piezoelectric devices have a pyroelectric output and the phase determining parameters are sensitive to temperature changes. This later factor is important since it can be presumed that the transducers will be used in arrays to determine the direction of the source from phase information. If the low frequency response is limited to 5 Hz, the piezoelectric microphone will have satisfactory phase performance. Using a piezoelectric microphone eliminates the need for a dehumidifier or for the high frequency carrier excitation that the condenser microphone needs in its design to insure long term stability.

The Soviet Union has been a purchaser of acoustic instrumentation from the Bruël and Kjaer Corporation in Denmark. This indicates that they probably have not been manufacturing laboratory standard quality instruments. Since high quality carrier operated capacitive transducers for the monitoring of atmospheric signals down to 0.01 Hz is commercially available from firms such as Bruël and Kjaer, it is reasonable that this equipment could be purchased for prototype system development. The Soviet Union has, in fact, obtained this technology by sending engineering personnel to Bruël and Kjaer to study the manufacturing process. This is documented by V. M. Mamin and A. M. Naumenko (1988). The countries of Eastern Europe, particularly Czechoslovakia, are an additional source of transducer engineering and manufacturing technology for the Soviet Union.

C. DISCUSSION OF SOVIET RESEARCH

Since the literature search has yielded little data on transducers designed specifically for atmospheric acoustics, it is necessary to measure Soviet capabili-

ties in this area from their literature on acoustic transducers in general. The Soviet literature covering general acoustic technology is extensive and appears to mirror Western literature. Table VI.2 indicates how the Soviet atmospheric acoustic literature can be divided by application.

Table VI.2
TRANSDUCER LITERATURE BY APPLICATION

A. Ultrasonic
   1. Non-Destructive Test
   2. Acoustic Emission
   3. Surface Wave Acoustic Devices
   4. Medical
   5. Materials Studies

B. Audio
   1. Studio
   2. Telephone-Communications
   3. Environmental
      a. Community Noise Monitoring
      b. Health Monitoring
      c. Vehicle Noise Suppression

C. Infrasonics
   1. Atmospheric Acoustics

1. Ultrasonic Transducers

The preponderance of the Soviet acoustic research related to transducers deals with ultrasonic applications. These can be divided into four large groups which total 80 percent of the papers reviewed: nondestructive test, surface wave acoustic devices, acoustic emission, and ultrasonic propagation in solids. Most of the acoustic transducers reported for this application are piezoelectric types. This large number of papers indicates that the Soviet Union has a broad technology base for piezoelectric design. There is an indication that polymer piezoelectrics are also being used in new transducer designs (for example, Domarkas, 1975).

2. Audio-Range Transducers

In the field of audio transducers, that is, microphones and loudspeakers, there is little reported in the scientific journals. Loudspeaker engineering deals almost exclusively with moving coil magnetic transduction, which does not lend itself to the development of atmospheric transducers due to the poor infrasonic frequency response of magnetic transducers of practical size.

The audio microphones reported have been mostly piezoelectric and condenser devices. The development of electret condenser microphones in the West during the early 1960s spawned a number of Soviet studies on practical designs, (Gorelik, 1974; Malinin, 1983). Estimates of the stabilities and lifetimes for electret materials were derived from physical principles (Kuzmin and Tayrov, 1983). Electret devices could serve as atmospheric acoustic transducers, but their environmental robustness leaves something to be desired. Several studies on the optimization of condenser microphone geometry indicate that the design of condenser microphones is well understood (Malinin, 1983; Vakhitov and Iofe, 1983).

3. Infrasonic Transducers

In the area of infrasonic microphones, only one paper was found. This deals specifically with the optimization of condenser microphones for infrasonic acoustics (Mamin, 1988).

There is considerable literature published on environmental studies, but the type or manufacturer of the microphones is not given. Presumably, a condenser microphone similar to the Bruël and Kjaer unit manufactured in Denmark is used. Such equipment is indicated in the East German literature, and could be supplied to the Soviet Union.

Very little work has been reported on commercially important magnetic or capacitive transducers. This may be due to the absence of journals dedicated to telephone and consumer type products.

The literature from research journals and technical conferences contains little material to indicate the state of the manufacturing art. Rather, the scientific literature indicates the emphasis on new technologies in which Soviet researchers expect to provide breakthroughs in either performance or cost. If information exists on the manufacturing technology, it may be found in journals dealing with production that are not covered in Western databases.

D. PROJECTIONS FOR THE FUTURE

The Soviet Union might be expected to be reporting research on micromachined silicon as a transducer technology for condenser microphones. This technology, reported for the past five years in the Western literature, allows precision capacitive transducer assemblies to be replaced by a silicon device manufactured with semiconductor processing equipment. This process eliminates the high skill levels previously needed to fabricate condenser microphones and produces a more uniform product. The current state of the art in the Soviet Union is not known from the literature, but several teams in Western Europe and the United States are working on silicon designs for mass production. The next step in this technology would be to integrate the electronics directly on the transducer silicon to form a monolithic transducer system. Such technology would require about five years of development.

E. KEY SOVIET LITERATURE

The most significant literature has been mentioned in the previous sections. The references from Soviet physics acoustics tend to address scientific research and do cover recent developments in transducer engineering.

Approximately 700 abstracts covering the general transducer field were reviewed. Eighty percent of the papers covered research and patents in the ultrasonic field. Among these were papers concerning surface wave acoustic devices, non-destructive tests, acoustic emissions, and most piezoelectric transducer applications. The next most published area was in optoacoustic transducers, followed by an assortment of transducers intended for audio range applications.

A large portion of the work reported is of an advanced nature and derives from universities or government laboratories. Typically, it appears that a professor's and his students' research is reported. Typically, three to five authors are listed. This indicates that work is being performed by teams, rather than by individuals.

F. KEY SOVIET RESEARCH PERSONNEL AND FACILITIES

Table VI.3 presents a list of key Soviet research personnel and facilities involved in transducer research.

Table VI.3
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—TRANSDUCERS

Electrical Engineering Institute im. V. I. Lenin, Leningrad

D. B. Dianov
A. G. Kuzm'enko
Yu. I. Kuz'min
V. N. Tairov

Polytechnic Institute im. Snechkus, Kaunas

V. I. Domarkas
R.-I. Yu. Kazhis

Acoustics Institute im. N. N. Andreyev, AS USSR, Moscow

E. V. Grischenko

Radio Engineering and Electronics Institute, AS USSR, Moscow

Yu. V. Gulyayev
I. M. Kotelyanskiy

State Scientific Research and Design Institute of the Rare-Metal Industry

I. N. Kanevskiy

Table VI.3
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES—TRANSDUCERS (cont'd.)

Dal'standardt Scientific-Industrial Union

B. A. Kasatkin

Semiconductor Physics Institute, AS USSR, Novosibirsk

V. A. V'yun
I. B. Yakovkin

Moscow Technological Institute of Food Industries

A. M. Naumenko

Radio Broadcasts Reception and Acoustics SRI im. A. S. Popov, Leningrad

V. K. Iofe

Aviation Institute im. N. Ye. Zhukovskiy, Khar'kov

A. M. Naumenko

Leningrad Institute of Motion Pictures Engineering

Sh. Ya. Vakhitov

All-Union Institute for the Improvement of Professional Skills for Leaders and Engineering Technical Workers in the Field of Standardization of Product Quality and Metrology

N. A. Konkov
A. M. Polikarpov

All-Union Institute for Investigation of Current Sources for Construction and Technology Projects

V. M. Mamin

All-Union Cinematography Scientific Research Institute, AS USSR

V. M. Gorelik
V. V. Usachev
A. E. Shrabyman
K. V. Neverovskiy

(blank)

CHAPTER VI: MICROPHONE TECHNOLOGY
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CHAPTER VII
PROCESSING OF ACOUSTIC SIGNALS

A. SUMMARY

The state of Soviet signal processing technology is sufficient to support the development of ground-based acoustic air surveillance systems. Basic algorithms are well known and would be the least limiting system development factor. Cost-effective, real-time implementation is probably more of a limitation, but is well within the present Soviet technological capabilities. Digital implementation, using integrated circuit chips comparable to those available in the United States in the middle to late 1970s, appears to be the best technology option available to the Soviet Union. Optical (analog) processing might also be considered, but optical processors are probably better suited to applications which require more processing power and can justify the cost of optical processing systems.

Some additional points are also important to note. First, the required signal processing technology is not particularly demanding or highly specialized for this problem. There are many elements in common with underwater acoustic surveillance and passive electromagnetic surveillance systems. The details are different for the different applications, but the basic algorithms and concepts are similar. Second, it would have been surprising to find much Soviet literature with an explicit connection to aeroacoustic surveillance. This is a tiny application area. Even in the United States and Western Europe, where we know there is research, there is very little available in the literature with explicit reference to the aeroacoustic surveillance application.

B. TECHNICAL BACKGROUND

The use of acoustic signals for air defense applications requires algorithms to perform functions such as detection, direction finding, localization, and recognition. In addition, it requires real-time analog or digital implementation of the algorithms. The subjects of this section are those algorithms and technology for their real-time implementation with a reasonable amount of hardware.

One way to perform aeroacoustic detection and direction finding is to use small arrays of microphones. An array of three or more microphones deployed over a small area a few meters in extent can be used to detect aircraft sounds and estimate their directions. The individual microphones do not need to be directional. A single array can cue other sensor and weapon resources, although it can provide only direction, not distance, and the warning time may be short for high-speed (but subsonic) aircraft.

The basic algorithms needed to detect targets and determine directions are essentially identical to algorithms used for underwater acoustic surveillance with a passive hydrophone array. The ideas are very simple. Microphone signals are first filtered to emphasize portions of the spectrum where signal-to-noise ratios should be largest. Then, for each direction of interest, time delays are calculated, relative to the arrival time at a reference microphone in the array, which should correspond to the delays experienced by signals coming from the direction of interest. The microphone signals are then shifted in time according to the delays and averaged. The resulting signal is called a beam. The signal from the direction of interest (if it exists) will add coherently in the beam while noise from other directions will be cancelled. Detection is performed on the basis of beam energy. Beams are formed for many different target directions. The beams with the largest energy are assumed to correspond to source directions.

Beamforming implementations are computationally dominated by the linear algebra operations of filtering, calculation of Fourier transforms, estimation of correlation functions, and calculation of quadratic forms. Optimized beamformers and other processing methods based upon the structure of microphone array correlation matrices may also require the decomposition and inversion of matrices in addition to the basic operations. The types of calculations required for detection and direction finding are well known and are common for many signal processing applications. Even non-array methods, for example, using signals from directional microphones to estimate source directions, tend to be dominated computationally by many of the same operations.

Unlike detection and direction finding, spatial localization and tracking require the use of two or more arrays, or the use of moving arrays, which is generally not practical for ground-based systems. The basic location algorithm is tri-

angulation, with some complexities introduced by acoustic delay effects for moving sources. Other algorithmic aspects of location and tracking are data association, data smoothing, and data extrapolation. Probabilistic and heuristic approaches are often used for data association; Kalman filters are the most common tool for smoothing and extrapolation. Although the details of aeroacoustic tracking are very different from those of other tracking systems, even underwater acoustic tracking systems, the basic methodology is essentially the same. No new theory is required, only the development of algorithms for the specific application.

Algorithms for acoustic recognition are much more specialized than those for detection, direction finding, and tracking. Recognition is a classification and pattern recognition problem, but most US work has been *ad hoc* and dependent upon specific domain knowledge about the sources. Algorithms exploit the spectral content of the signals and, therefore, depend upon signal processing algorithms such as filtering and spectral analysis. Essentially nothing significant about the development of practical acoustic recognition algorithms appears in the published US literature.

C. ALGORITHMS

The basic algorithm papers generally fit into two broad categories—array processing and source location. For array processing, the intended acoustic application appears to be underwater acoustic surveillance. For source location, the applications appear to be underwater surveillance and, probably, aeroacoustic weapon location.

Since beamforming is a well-known standard array processing method, it is not surprising that the papers about this topic produce no major surprises. It is clear that not only the basic ideas, but some of the important practical issues, are well understood. For example, an early paper by Abramov and Podol'skiy (1972), a later one by Aleshchenko et al. (1983), and a very recent one by Leykin (1987) are all indicative of the fact that the Soviet Union has been and continues to be concerned about practical issues such as directivity pattern smearing for wide-band signals and the performance loss due to Doppler shifts for moving sources. Near-field noise immunity, the effect of near-field noise sources on array per-

formance, appears to receive considerable attention but this may be misleading, since three of the four papers have a common author.[1] An interesting aspect of the Smaryshev paper (1987) and an earlier one in 1985 (Smaryshev and Shenderov, 1985) is the consideration of dipole and cardiod sensor elements, as well as monopoles. The attention to near-field noise immunity is probably motivated by a concern for self-noise in underwater acoustic applications, both active and passive.

Several papers deal with optimum array design, that is, the selection of filters and signal weightings to improve directivity and enhance noise immunity. Two kinds of papers are included: classical array design papers, and papers dealing with adaptive array processing. The classical papers (Karnovskiy et al., 1983, 1987; Zhukov et al., 1982) concentrate on designing array weights to optimize array performance for average conditions. Typically, low sidelobes and good directivity are emphasized. This is very dated work (by Western standards), although the consideration of near-field interference is novel. The papers on adaptive processing which optimally reject interference (Lekhovitskiy and Rakov, 1986; Maslov and Nesterov, 1986), are more in line with the emphasis in the Western research community. (The Maslov paper is concerned with phased array radars, but is equally applicable to acoustic arrays.) Other papers dealing with adaptive methods are oriented more toward digital implementation technology and are discussed in the section dealing with digital implementation (Section VII.D).

Several papers deal with the use of acoustic sensors to locate sources (in two dimensions).[2] Methods include time-difference-of-arrival techniques and triangulation of direction measurements obtained using arrays. The Gershman paper explicitly mentions sound ranging (weapon location) as an application area (Gershman and Shikalov, 1977). The Katulev paper is the only paper which considers the motion of the source (Katulev and Tukhvatulin, 1986). It proposes exploiting the source (or sensor) motion as a technique for de-ghosting in a multi-target environment. (In multiple-source environments, the direction

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1 Karnovskiy and Shotskiy, 1983; Karnovskiy et al., 1983, 1987; Smaryshev, 1987.

2 Gershman and Shikalov, 1977; Katulev and Tukhvatulin, 1986; Krasnyy and Skripchenko, 1979; Pudovkin, 1980.

measurements from different arrays may be incorrectly associated, resulting is "ghost" targets when locations are estimated using triangulation and the wrongly associated measurements.) In all cases, the emphasis is on a small number of sensors or a small number of arrays (two or three). The emphasis is on the situation where the sensors are deployed over an area of extent L and the sources of interest are located from a few to several tens of L's distant from the sensors. Thus, Soviet researchers appear to be interested in relatively small and geographically localized systems rather than large distributed networks, where sensors would be deployed in all directions around the sources. There is no mention of target tracking in these papers, although the Katulev paper implies a trivial level of tracking by assuming constant-bearing, constant-velocity tracks for the purpose of de-ghosting. All of this work is straightforward. There is no indication of interest in multi-site tracking of targets, such as aircraft, where the velocity of the target can be significant relative to the velocity of propagation of sound.

D. DIGITAL IMPLEMENTATION

If the Soviet literature reviewed is indicative, the early to middle 1980s was a period when medium- and large-scale integration and microprocessors came of age and became available for widespread use for signal processing as well as for other applications. The paper "Microprocessor Techniques—The Basis of Technical Progress in the Eighties" by Proleyko (1983) captures apparent enthusiasm for the development of digital embedded systems. The title of the "Digital Signal Processing" paper by Varakin (1984) masks an equally enthusiastic pep talk on the virtues of digital signal processing for many applications. It presents the merits of digital processing versus analog processing, a discussion that might have been seen in a US journal in the middle 1970s.

More directly of interest, several papers are specifically concerned with the application of digital signal processing methods for array processing. Papers by Struchev (Struchev, 1984; Struchev and Levshin, 1985) and Glushankov (1984) concern parallel implementation architectures and the structuring of algorithms for efficient digital implementation, respectively. An interesting aspect of these papers is that they take for granted adaptive array processing algorithms, thereby suggesting that such algorithms are widely known and used. The Struchev

paper emphasizes parallel architectures and specialized processors for adaptive array processing. The emphasis is on very high data rates and computational requirements, several orders of magnitude more than would be required for an aeroacoustic array. The application is more likely phased array radars or very large hydroacoustic arrays. The Glushankov paper is oriented more toward the practical implementation of adaptive algorithms using available technology without massive parallelism and is sensitive to weight, cost, and energy constraint issues (Glushankov, 1984). Two other papers consider not only beamforming, but are also concerned with the possible loss of performance due to signal quantization (Kazmirtsak and Tyutekin, 1985; Gatkin et al., 1982). However, these four papers are theoretical and do not provide information about implementation technology.

Other papers do contain somewhat more information about chips and implementation details. A fair amount of information about integrated circuit chips and their use for digital signal processing is contained in Glushankov and Davydenko (1983). Several papers concerning different signal processing applications also provide information about the technology. These include five communication application papers,[3] two radar signal processing application papers (Bystrov and Nezlin, 1987; Gavrilenkova et al., 1983); and even a consumer product application (Rivkin and Urik, 1983), although in this latter case, the microprocessor does not perform signal processing. The enthusiastic paper by Proleyko (1983) also contains some information about chips.

As reported in the Soviet literature, the two main types of processors used for digital signal processing work appear to be the K589 and K1804 bit-slice microprocessors. Both are bipolar devices similar in nature to the AMD 2901 microprocessor that the United States started to use in the middle to late 1970s. These microprocessors appear in the Soviet literature as early as 1983 and as late as 1988. The K589 has a 100-nanosecond (nsec) cycle time and is a 2-bit ALU slice. The K1804 is a 4-bit slice with a 150-nsec cycle time. The K1804 has more internal registers than does the K589 (the exact number is not mentioned, but is probably 16).

3 Bakharev and Fomin, 1987; Gorodilin and Glushankov, 1984; Kharisov et al., 1984; Mikhov, 1986; Sotnikov, 1983.

These bit slices can be cascaded together to form the desired word width, but the cycle time must be extended if too many are cascaded together (probably four is the maximum). The devices must be microprogrammed. They do not contain hardware multipliers. Shift and add routines are used for multiplication. One article mentions a parallel multiplier (1802VR3), but does not mention its work size, although one can probably assume that a reasonable speed (200 nsec) 16-bit multiplier is available. All these devices fit into our class of large-scale integration bipolar microprocessors. These devices are quite adequate to build the basic signal processor for acoustic direction finding.

The Soviet literature also mentions single-chip microcomputers that are available (Gal'perin et al., 1984; Glushankov and Davydenko, 1983; Pogorelov et al., 1987). They are made of p-channel metal-oxide semiconductor circuitry and n-channel metal-oxide semiconductor circuitry and are relatively slow (2 to 4 μsec execution times). This may be the best that the Soviet Union now possesses because the 1987 Pogorelov article concerns a paging technique for memory accessing which overcomes the 16-bit limitation. These microcomputers do not have much processing power and are used mainly as device controllers. The Gal'perin paper indicates that the Soviet Union also has single-board computers, but no mention is made of their design or processing power. It appears that the Soviet Union has not yet reached the stage of readily available very-large-scale integration processors. No mention is made of a floating-point multiplier or complete processor chips. These were developed in the United States a few years after the introduction of very-large-scale integration technology. The Soviet single-chip microcomputers and single-board computers probably could be used, in addition to bit-slice processors, for the more demanding signal processing tasks—to implement a practical acoustic detection, direction finding, and source location system.

The availability of chips and processors is only part of what is needed to develop a system. This was clearly recognized in an interesting article entitled "The Problems Involved in Developing and Using Microprocessors" written by Shats and Khamilevich (1983). The article identifies all the major problems involved in microcomputer development and debugging, especially in the software area. The authors recommend that more courses be taught in universities and more literature be published in this area. Similar articles could be found in

the US literature in the middle 1970s. Assuming that Soviet researchers took their own advice, by now they should be well equipped to handle microprocessor system development and digital signal processing work. Other papers appearing in the 1983 to 1984 time frame also recognize the importance of hardware and software development tools and techniques.[4]

One paper by Bunkin et al. (1988) describes a 48-channel hybrid analog-digital acoustic beamforming processor which was tested with a 20-element hydroacoustic array. The system is a narrow-band system using phase shifts rather than delays and can switch between four different predetermined beam directions. It is predominantly analog, without any digital signal processing, and fairly unsophisticated. A microcomputer is used to control and obtain data from the system. It certainly is not representative of the digital capabilities and algorithmic sophistication evident in many other papers. But it is the only specific example found of an acoustic implementation.

E. OPTICAL IMPLEMENTATION

Optical processing is obviously of great interest in the Soviet Union, and Soviet research is quite technologically advanced in the field. The interest includes general-purpose processing, general signal processing, and array processing in particular. Review and tutorial papers, although emphasizing theory rather than implementation, present some feeling for the broad interest in the Soviet Union.[5] Applications of great interest appear to include communication and radar signal processing and acoustic nondestructive testing. Optical processing is a large and important technology area. A comprehensive survey and evaluation is beyond the scope of this report and has not been attempted.

Signal processing for acoustic arrays is clearly an application of interest, although the focus appears to be hydroacoustic arrays and arrays for nondestructive testing which can involve high acoustic frequencies and near-field phenomena. The paper by Mel'treger and Kheyfets (1979) represents the work that was

4 Kaninskiy and Teslyuk, 1984; Murenko et al., 1983; Rachimbekov and Varfolomeyev, 1984.

5 Bakhrakh et al., 1982; Gulyayev et al., 1987; Yezhov and Tarasov, 1980; Zosimov and Lyamshev, 1986.

found to match most closely the aeroacoustic problem, although it clearly applies equally to hydroacoustic arrays. The paper describes a simple optical system for beamforming a linear acoustic array. No significant technical implementation or performance details are provided, although simple experimental results are shown to indicate that an experimental system exists. A paper by Lapides et al. (1983) also describes an optical method for determining the direction of acoustic noise sources using microphone arrays, but it is a non-real-time laboratory method which requires using the acoustic signals to modulate a photographic film. The application is the analysis of room and industrial noise. Other papers were found which concentrate on the theoretical aspects of acoustic direction finding in a homogeneous medium (Svet, 1982), and on acoustic direction finding in a waveguide. Svet, who is well-known in the field of Soviet acoustic processing, is also a coauthor of the waveguide papers by Bayramkuliyev et al. (1984) and Zuykova and Svet (1981, 1987). The 1987 Zuykova and Svet paper concerns a hybrid digital-optical system which combines "the algorithmic versatility and precision of digital devices with the high speed and efficiency of coherent-optics techniques."

Most of the Soviet literature is highly theoretical and contains no information about the actual state of real devices or systems. However, based upon US technology, we would expect that optical systems would tend to be expensive high-performance systems, not particularly well matched to the modest requirements of an aeroacoustic surveillance system. The information contained in the Soviet literature is consistent with this view, but insufficient technical detail was found to confirm it.

F. PROJECTIONS FOR THE FUTURE

There clearly is a strong trend toward digital signal processing methods and embedded computers for many applications. The factors limiting the adoption of digital methods are technological, not algorithmic. Larger memory chips, floating-point hardware for small systems, higher level implementation languages, and debugging tools for microprocessor systems would make what is now a feasible but difficult task into relatively straightforward development tasks.

Optical processing methods should also continue to receive much attention, but processing of acoustic data for aeroacoustic surveillance is probably not a primary application. More likely, applications are radar and large underwater acoustic arrays. These have much larger real-time processing requirements and less stressing operational environments than are likely for the aeroacoustic application.

For either digital or optical systems, the need for acoustic surveillance is not for massive processors, but for large numbers of modest processors in small rugged packages.

CHAPTER VII: PROCESSING OF ACOUSTIC SIGNALS

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CHAPTER VIII
ACOUSTIC-GRAVITY WAVES AND IONOSPHERIC DETECTION

A. SUMMARY

This chapter examines Soviet research of acoustic-gravity waves and ionospheric detection. It is well known that low-altitude sources produce gravity waves which perturb the ionosphere. These perturbations can be detected by Doppler shifts in radio waves reflected off the ionosphere. Whether or not these phenomena can be used for aircraft detection is not clear, since the background noise levels in the ionosphere are quite high.

It is clear that the Soviet Union is very active in ionospheric research. Four major institutes are involved in the detection of ionospheric disturbances. There is much activity concerning the theoretical prediction of the generation and propagation of acoustic gravity waves.

Ionospheric research is well supported in the Soviet Union. If this technique can be exploited to detect aircraft, the Soviet Union has the manpower and capability to do so. This is a useful method for the detection of large explosions, since the perturbations from atmospheric and underground tests can be easily measured.

B. OVERVIEW

The ionosphere has been the subject of much research by the scientists interested in radio wave reflection off the ionized layer. In this report, we will concentrate on the possible detection of lower altitude disturbances by the reflection of radio waves from the ionosphere.

The prototype interaction is the detection of a large explosion by the behavior of the reflection of short radio waves off the ionosphere. Such explosions produce acoustic and acoustic-gravity waves. At low frequencies, the acoustic wave couples into the buoyant restoring force of gravity on the atmosphere and two modes result. At very low frequencies ($\sim 10^{-2}$ Hz), the propagation is dominated by the buoyant force (internal gravity waves). At higher frequencies, the wave

behavior is primarily acoustic. The critical frequency between these two modes is the Brunt-Väisälä frequency:

$$\omega_b^2 = (\gamma - 1)\, g^2/c^2 + \frac{g}{c^2}\frac{dc^2}{dz}.$$

Ionosphere disturbances corresponding to internal gravity waves have been detected from large explosions, earthquakes, reentry vehicles, launch vehicles, and storms. Higher frequency disturbances have been observed corresponding to acoustic waves, but these disturbances have not been correlated to particular sources.

The detection of high-frequency (> 1 Hz) acoustic waves in the ionosphere is unlikely due to sound absorption. Absorption in the upper atmosphere is quite large since attenuation per unit wavelength scales as f/p, where f is the frequency and p is the atmospheric pressure. A 1-Hz signal at 160 km is attenuated at the same rate per unit wavelength as 333 MHz at sea level.[1] This effect limits the acoustic modes of interest to the infrasound range.

Horizontally traveling sources have been investigated theoretically. Supersonic sources will produce both acoustic and internal gravity mode disturbances, while the gravity mode will dominate for subsonic sources.

The key to detection by ionospheric disturbance is the same as any detection problem: will the source produce a large enough disturbance to be detected in the frequency range of interest?

The following section reviews Soviet research about the generation of acoustic-gravity waves and the detection of disturbances in the ionosphere by radio wave reflection.

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1 J. H. Gardner, and P. H. Rogers, "Thermospheric Propagation of Sonic Booms from the Concord Supersonic Transport," NRL Memorandum Report 3904, Office of Naval Research, 14 February 1979.

C. DISCUSSION OF ACOUSTIC-GRAVITY WAVES AND IONOSPHERIC DETECTION

The Soviet Union has a very active program in ionospheric research and aeronomy. The Radiophysics Scientific Research Institute in Gor'kiy, the Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation Institute of the Siberian Department of the Soviet Academy of Sciences in Irkutsk, and the Ionosphere Research Institute of the Academy of Sciences of the Kazakh Soviet Socialist Republic (KaSSR) all have active programs in the generation of acoustic gravity waves and their effect on the ionosphere.

Recent emphasis in the Soviet Union has been on the generation of internal gravity waves by large explosions. The Siberian Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation Institute, and the Ionosphere Research Institute of the Kazakh Academy of Sciences have performed several measurements of the ionospheric effect of explosions. In November 1981, explosions were fired in the Alma-Ata region, in April 1982 in the Slyudyanka region, and in October 1984 near Bukhara in the Uzbek Soviet Socialist Republic (UzSSR).

On a long-time scale (3.6-minute sample rate), incoherent scatter was monitored during the Slyudyanka explosion and changes were noted (Abramov et al., 1983). Higher resolution data on the same explosion were also obtained using Doppler radar. The amplitude and frequency of the ionospheric perturbation were calculated from atmospheric models and agreed well with the data. The perturbations occurred on a time scale of tens of seconds, indicating that these waves are in the acoustic branch of the dispersion curve, rather than in the internal gravity wave branch (Varshavskiy and Kalikhman, 1984). A more detailed model including nonlinear propagation effects is presented in the article by V. V. Orlov and A. M. Uralov (1984). This paper calculates the expected Doppler frequency shift magnitude for a range of explosion sizes. The smallest explosion considered is 24 tons of explosives. For this amount of explosive, the wave period is approximately 10 seconds.

A similar theoretical calculation which employs numerical methods for predicting the nonlinear evolution of the acoustic-gravity waves was performed by Ye. A. Rudenchik and V. V. Solov'yev (1987).

The most recent experiment was the October 1984 experiment reported by scientists from the Ionosphere Research Institute of the Kazakh Academy of Sciences. In this paper, the authors compare the results from a small explosion (~ 60 tons equivalent) with the earlier Alma-Ata experiments. The Doppler devices used two frequencies, 2.0 MHz and 4.9 MHz. Results similar to earlier tests were obtained, as well as recordings of magnetic field variations (Drobzhev et al., 1987). This measurement indicates that energy releases on the order of 3×10^{11} joules (~ 60 tons) easily produce detected changes in Doppler radio ionograms.

Of more interest is the detection of lower energy disturbances by Doppler radar. V. V. Kulikov et al. (1982) report ionospheric perturbation due to the fall of Skylab. Skylab burned up at 10 to 20 km and produced significant internal gravity waves at several observatories in the Soviet Union. The energy of this event was estimated as 10^{12} to 10^{13} joules. The frequencies detected correspond to the internal modes at approximately 1.6×10^{-2} Hz.

Theoretical work is reported on the infrasound and internal gravity waves produced by lightning (Grigor'yev and Dokuchayev, 1981). The energy release in this case is approximately 10^9 joules, which produces ionospheric perturbations in the 0.01 to 1-Hz range with magnitudes on the order of 10^{-2} dyne/centimeter. The paper concludes that the acoustic-gravity perturbation near the Brünt-Väisälä frequency may be detectable.

Theoretical work has been performed on the generation of acoustic-gravity waves by moving sources. G. I. Grigor'yev et al. (1979) predict that horizontal supersonic sources will produce both internal gravity waves and acoustic-gravity waves, and the subsonic sources will produce only internal waves. A. P. Slivinskiy (1983) predicts that vertical supersonic sources will produce 10-percent density fluctuations on the ionosphere with an energy release of 10^9 joules/second. The perturbations are internal waves with frequencies near the Brünt-Väisälä frequency.

The literature search on the subject of ionospheric detection revealed many Soviet articles concerning acoustic-gravity waves and ionospheric research

which did not have a direct bearing on detection. This body of literature does provide much information about Soviet capabilities. The Soviet Union has always had a strong research program in wave propagation, plasma physics, and atmospheric physics. In the recent papers, these institutes have shown strong experimental, analytical, and numerical approaches to ionospheric research.

A very advanced program of strong radio wave effects and ionospheric modification is being conducted in the Soviet Union. In these experiments, a strong beam perturbs the ionosphere and a weaker probe beam is used to probe the disturbances.[2]

Theoretical work is performed at the institutes of the Soviet Academy of Sciences and also at the universities.[3] These works are natural extensions of previous Soviet work on wave propagation.

It is surprising that the Soviet Union also has a very strong program in numerical calculations of finite wave propagation in the atmosphere. In addition to the numerical techniques used in papers above (Rudenchik and Solov'yev, 1987; Orlov and Uralov, 1984), work on numerical methods and errors in numerical methods are presented by V. A. Belov and A. G. Kolesnik (1983) of Tomsk State University and N. M. Kashchenko and M. A. Nikitin (1986) of Kaliningrad State University.

D. PROJECTIONS FOR THE FUTURE

The Soviet Union has a long history of support for research on the ionosphere and the detection of acoustic gravity waves. The application of this technique to the remote sensing of explosions is of sufficient importance to guarantee continued support for experimental and theoretical work in these fields. If an aircraft detection scheme can be developed based on these principles, the Soviet Union will be able to do so.

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2 Novozhilov et al., 1984; Karlov et al., 1985; Bakhmet'yeva et al., 1985, 1986; Chernogor, 1985.

3 Gusev and Radzhabov, 1983; Gusev and Makhmutov, 1984; Gvelesiyani and Keshelashvili, 1985.

E. KEY SOVIET LITERATURE

The key Soviet literature is presented in the references section at the end of this chapter. The most important of these is the article by Rudenchik and Solov'yev (1987), entitled "Evolution of Short-Wave Acoustic Disturbances in the Atmosphere and Their Structure at Ionospheric Altitudes," which demonstrates interest in relatively short wavelength waves. The calculations of the finite wave effects are quite sophisticated.

F. KEY SOVIET RESEARCH PERSONNEL AND FACILITIES

A listing of key Soviet research personnel and facilities involved in acoustic-gravity wave and ionospheric detection work is presented in Table VIII.1.

Table VIII.1

KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— ACOUSTIC-GRAVITY WAVE AND IONOSPHERIC DETECTION

(* indicates leading personalities)

Radiophysics Scientific Research Institute, AS USSR (Gor'kiy), Gor'kiy State University im. N. I. Lobachevskiy, Gor'kiy

N. V. Bakhmet'yeva	Yu. A. Ignat'yev
V. V. Belikovich*	Yu. V. Mitukhin
M. G. Deminov	O. N. Savina*
V. P. Dokuchayev*	V. V. Tamoykin
G. I. Grigor'yev*	

Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation Institute, AS USSR, Troitsk (affiliate in Leningrad)

M. G. Deminov	A. V. Shirochkov
F. G. Deminova	I. A. Shumilov
D. I. Fishchuk	V. V. Solov'yev
V. V. Kulikov	Ye. Ye. Tsedilina
B. Yu. Nekrasov	I. A. Tushentsova*
Ye. A. Rudenchik	L. M. Yerukhimov
V. M. Shashun'kina*	L. A. Yudovich*
B. S. Shapiro	

Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation Institute (Siberian), AS USSR, Irkutsk

V. G. Abramov	V. V. Orlov
D. K. Danovich	A. M. Uralov
A. D. Kalikhman	I. I. Varshavskiy
A. N. Klimov	B. N. Velichanskiy*
V. N. Kulagin*	A. V. Zaborin
N. V. Larionov	

Ionosphere Research Institute, AS KaSSR, Alma Ata

V. I. Drobzhev	G. M. Pelenitsyn
M. A. Kaliyev	N. M. Salikhov
V. V. Kazakov	V. L. Savelyev
V. M. Krasnov	A. D. Shingarkin
I. K. Idrisov	Ye. V. Zheleznyakov

Table VIII.1
KEY SOVIET RESEARCH PERSONNEL AND FACILITIES— ACOUSTIC-GRAVITY WAVE AND IONOSPHERIC DETECTION (cont'd.)

Applied Mathematics Institute im. M. V. Keldysh, AS USSR, Moscow

Yu. I. Galperin*
G. S. Golitsyn*
A. V. Kolesnichenko
M. Ya. Marov
N. N. Shefov

General Physics and Wave Processes Department, Moscow State University im. M. V. Lomonosov, Moscow

V. D. Gusev*
N. A. Makhmutov
T. S. Radzhabov

Khar'kov State University im. A. M. Gor'kiy, Khar'kov

L. F. Chernogor
V. D. Karlov
V. I. Novozhilov*
G. N. Tkachev
S. I. Trubayev*
A. A. Vergasov

Atmospheric Physics Institute, AS USSR, Moscow

A. V. Danilov
A. V. Dovzhenko

Kaliningrad State University, Kaliningrad

N. M. Kashchenko
M. A. Nikitin

Siberian Physical Technical Institute im. Kuznetsov, Tomsk (located at Tomsk State University)

V. A. Belov
A. G. Kolesnik

Geophysics Institute, AS GeSSR, Tbilisi

G. V. Dzhandiyeri
A. I. Gvelesiyani
Dzh. R. Keshelashvili

Civil Aviation Engineers Institute, Riga

A. I. Aleksandrov
Yu. A. Krasnitskiy

CHAPTER VIII: ACOUSTIC-GRAVITY WAVES AND IONOSPHERIC DETECTION

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APPENDIX A
ABOUT THE AUTHORS

Henry E. Bass *(Chairman).* Dr. Bass is currently on sabbatical leave at the Naval Postgraduate School from the University of Mississippi. At the University of Mississippi he is F.A.P. Barnard Distinguished Professor of Physics and Director of the Physical Acoustics Research Center. He received a PhD in Physics from Oklahoma State University in 1971 where he was an NSF Fellow. Since joining the faculty at the University of Mississippi in 1971, his research has been concerned with microscopic processes in sound propagation. He received the Biennial Award in acoustics from the Acoustical Society of America in 1978 for work in outdoor sound propagation. He is a US member of NATO research study group RSG-11 concerned with tactical battlefield surveillance using mechanical waves. Dr. Bass is a Fellow of the Acoustical Society of America, and Associate Editor of the Journal of the Acoustical Society of America, and a Lieutenant Colonel in the US Army Reserve.

Richard T. Lacoss. Dr. Lacoss leads the Machine Intelligence Technology Group at the Massachusetts Institute of Technology's Lincoln Laboratory. He received his PhD in Electrical Engineering from the University of California at Berkeley and joined the staff of Lincoln Laboratory in 1965. He has extensive signal processing experience, including research involving seismometer arrays for nuclear test monitoring, and development of aeroacoustic surveillance methods. Dr. Lacoss became Associate Leader of the Applied Seismology Group in 1972, and in 1982 formed a new Distributed Sensor Systems Group whose activities included research into ground-based aeroacoustic surveillance. This group was expanded in 1987 and became the Machine Intelligence Technology Group. Other projects for which Dr. Lacoss is now responsible involve neural networks, expert systems to control communication networks, radar data interpretation algorithms, and parallel processors for real-time implementation of data interpretation algorithms. Dr. Lacoss has taught signal processing at the Massachusetts Institute of Technology and has authored more than 25 published articles, reports, and book chapters. His professional memberships include the Institute of Electrical and Electronic Engineers, the Association for Computing Machinery, and Sigma Xi. He has been an officer of the IEEE Geoscience Electronics Group and a technical editor for its transactions. He was a member of the Digital Signal Processing Committee of the IEEE Acoustics Speech and Signal Processing Society from 1983 to 1987 and was Chairman of its 1986 DSP workshop. He has been an invited lecturer in signal processing at NATO Advanced Study Institutes in Norway (1974) and Italy (1976).

Thomas E. Landers. Dr. Landers graduated from Stanford University in 1971 where he earned a PhD in Geophysics. His thesis concerned numerical solutions to the nonhomogeneous elastic wave equations. He received a BS from San Jose State College in 1966 in Geophysics. In 1971, he joined the Massachusetts Institute of Technology's Lincoln Laboratory as a member of the technical staff in the Seismic Discrimination Group. In 1977, he helped create the DARPA Distributed Sensor Networks Program at Lincoln Laboratory. This work led to the creation of the Distributed Sensor Systems Group at Lincoln Laboratory in which he served as the Assistant Group Leader until 1984. He then joined the Northrop Corporation as the Director of the Sensor Technology Group at the Electro-Mechanical Division in Anaheim, California. He currently is responsible for managing the division's research, development, and engineering activities in sensor signal processing, transducers, aerophysics, and systems development. He is currently active in the following professional societies: the Institute of Electrical and Electronic Engineers, the Acoustical Society of America, the American Geophysical Union, the American Institute of Aeronautics and Astronautics, the American Defense Preparedness Association, and the Society of Exploration Geophysicists.

Alan Powell. Dr. Powell is a Professor in the Department of Mechanical Engineering at the University of Houston. After working on aircraft design for the Percival Aircraft Company, he initiated research on jet noise and obtained his PhD at the University of Southhampton in 1953. He later joined the Douglas Aircraft Company, spending a year at the California Institute of Technology as a research fellow before moving to the University of California at Los Angeles, becoming Professor of Engineering in 1962. In 1965, he became head of the new Ship Acoustics Department at the David Taylor Model Basin, and Technical Director in 1966. He remained in that position through various reorganizations, which culminated in the now David Taylor Research Center, until he joined the University of Houston in 1986. One of his many visits abroad was to the Soviet Union in 1980, which included 10 days as the guest of L. M. Lyamshev of the Acoustics Institute im. N. N. Andreyev. He has been recognized by the Royal Aeronautical Society (Fellow, Baden-Powell and Wilbur Wright prizes), Acoustical Society of America (Fellow, Biennial Award), AIAA (Aeroacoustics Award), ASME (Rayleigh Lecturer), Loughborough University of Technology, UK (Honorary D. Tech.), the Secretary of the Navy (Captain Robert Dexter Conrad gold medal) and President Ronald Reagan (Meritorious Executive). He has served on numerous governmental and society bodies, including as Chairman of the NAS-NRC Committee on Hearing and Bioacoustics (CHABA) and, presently is the President of the Acoustical Society of America.

Richard Raspet. Dr. Raspet is an Associate Professor of Physics and Astronomy at the University of Mississippi. He received his PhD in 1975 from the University of Mississippi and served there as a Visiting Assistant Professor until May of

1978. Dr. Raspet was a physicist on the Acoustics Team of the US Army Construction Engineering Research Lab from 1978 to September 1987. Dr. Raspet received the US Army R&D Award in 1983 and the US Army Corps of Engineers Researcher of the Year Award in 1986. Dr. Raspet is a Fellow of the Acoustical Society of America.

James D. Revell. Dr. Revell is an R&D Scientist in the Acoustics Group of the Research, Technology, and Engineering Branch at the Lockheed Aeronautical Systems Company (LASC), Burbank, California. He has over 37 years of engineering experience. He received his BS in Engineering in 1952, his MS in Engineering, and PhD in Engineering Mechanics in 1966, all from UCLA. Currently, and since 1983, Dr. Revell has been the program manager and principal investigator of several classified research projects related to airborne acoustic detection of military aircraft, for NASA, the US Air Force, and Lockheed. Between 1977 and 1983, he was program manager and principal investigator of several research programs for NASA/Langley relating to interior noise of advanced turboprop and propfan aircraft. He has published over 30 papers on acoustics and aerodynamics, including some pioneering papers on airframe aerodynamic noise in the early 1970s. He first joined Lockheed in 1965 and participated in the sonic boom and unsteady aerodynamic studies for the SST, and in the aerodynamic wing design for the L-1011. He worked for Northrop (1960-1965), specializing in structural dynamics and acoustics, at North American (1957-1960) in flutter and aeroelasticity, and earlier at Northrop (1952-1957) in thermodynamics and propulsion. He is an Associate Fellow and member of the Aeroacoustics Technical Committee of the AIAA, a member of the Acoustical Society of America and the Society of Sigma Xi.

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APPENDIX B
GLOSSARY OF ABBREVIATIONS AND ACRONYMS

A-U	all-union
ALU	arithmetic logic unit
AMN	*Akademiya meditsinskikh nauk* (Academy of Medical Sciences)
AN	*Akademiya Nauk* (Academy of Sciences)
AS	Academy of Sciences
CFD	computational fluid dynamics
cm	centimeter
dB	decibel
EPA	Environmental Protection Agency
EPNL	effective perceived noise level
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FFP	Fast Field Program
ft	feet
GeSSR	Georgian Soviet Socialist Republic (Georgia)
H_2O	water
Hz	hertz
IC	integrated circuit
ICAO	International Civil Aviation Organization
J	joule
KaSSR	Kazakh Soviet Socialist Republic (Kazakhstan)
kHz	kilohertz
kW	kilowatt

LF	low frequency
LO	low observable
LSI	large-scale integration
MOC	method of characteristics
MSI	medium-scale integration
N	nitrogen
NASA	National Aeronautics and Space Administration
NMOS	n-channel magnetic oxide semiconductor
NOAA	National Oceanic and Atmospheric Administration
nsec	nanosecond
PE	parabolic equation
PMOS	p-channel magnetic oxide semiconductor
RAS	radio-acoustic sounding
RASS	radio-acoustic sounding
RF	radio frequency
SCAR	Supersonic Cruise Aircraft Research
SO	*Siberskoye otdeleniye* (Siberian department)
SODAR	acoustic sounding
SST	supersonic transport
STA	supersonic transport aircraft
TOGW	gross takeoff weight
UK	United Kingdom
UzSSR	Uzbek Soviet Socialist Republic (Uzbekistan)
VLSI	very-large-scale integration
VSTOL	vertical/short takeoff and landing
VUZ	*vyssheye uchebnoye zavedeniye* (higher educational institution)

VLSI	very-large-scale integration
VSTOL	vertical/short takeoff and landing
VUZ	*vyssheye uchebnoye zavedeniye* (higher educational institution)
µsec	microsecond

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APPENDIX C

SOVIET JOURNALS CITED IN TEXT/REFERENCES

For readers not familiar with the Soviet technical literature, a key to the abbreviated titles of the Soviet serial literature cited in this report is provided below. The titles of the English-language translations used are listed in **bold print** and the original Russian-language titles are in *italics*. When a given Soviet technical journal is published in more than one commercial translation, the English title for the same Soviet source may vary with the publisher. If translations have been made privately (for example, government agency translations), the titles may also vary. Frequently, English titles are not literal translations of the original Russian. Therefore, knowledge of the Russian title of a journal may be necessary to identify reference materials.

Abbreviation	English Translation Title/*Original Russian Title*
Appl. Math. Mech.	**Applied Mathematics and Mechanics** *Prikladnaya matematika i mekhanika*
Atmos. Oceanic Phys.	**Atmospheric and Oceanic Physics** *Izvestiya Akademii nauk SSSR, Fizika atmosfery i okeana*
Combust. Explos. Shock Waves	**Combustion, Explosion, and Shock Waves** *Fizika goreniya i vzryva*
Dokl. AS USSR	**Doklady Academy of Sciences** *Doklady Akademii nauk SSSR* (The *Doklady*-reports-are published in translation according to the specific fields to which they refer.) See Doklady Earth Science Section.
Dokl. Earth Sci. Sect.	**Doklady Earth Sciences Section** *Doklady Akademii nauk SSSR*
Eng. Cybern.	**Engineering Cybernetics** *Izvestiya Akademii nauk SSSR, Tekhnicheskaya kibernetika*
Fluid Dyn.	**Fluid Dynamics** *Izvestiya Akademiya nauk SSSR, Mekhanika zhidkostey i gaza*

Fluid Mech.-Sov. Res.	**Fluid Mechanics-Soviet Research**
Geomagn. Aeron.	**Geomagnetism and Aeronomy** *Geomagnitizm i aeronomiya*
High Temp.	**High Temperature** *Teplofizika vysokikh temperatur*
Izv. VUZ, Radio Eng.	**Izvestiya VUZ, Radio Engineering** *Izvestiya vysshikh uchebnykh zavedeniy, Radiotekhnika*
J. Appl. Mech. Tech. Phys.	**Journal of Applied Mechanics and Technical Physics** *Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki*
J. Eng. Phys.	**Journal of Engineering Physics** *Inzhenerno-fizicheskiy zhurnal*
Moscow Univ. Phys. Bull.	**Moscow University Physics Bulletin** *Vestnik Moskovskogo universiteta, Seriya 3: Fizika, astronomiya*
Radiophys. Quantum Electron.	**Radiophysics and Quantum Electronics** *Izvestiya vysshikh uchebnykh zavedeniy, Radioelektronika*
Sov. Aeronaut.	**Soviet Aeronautics** *Izvestiya vysshikh uchebnykh zavedeniy, Aviatsionnaya tekhnika*
Sov. J. Commun. Tech. Electron.	**Soviet Journal of Communications Technology and Electronics** (formerly **Radio Engineering and Electronic Physics**) *Radiotekhnika i elektronika*
Sov. J. Comput. Syst. Sci.	**Soviet Journal of Computer and Systems Sciences** (formerly **Engineering Cybernetics**) *Izvestiya Akademii nauk SSSR, Tekhnicheskaya kibernetika*
Sov. Meteorol. Hydrol.	**Soviet Meteorology and Hydrology** *Meteorologiya i gidrologiya*

Sov. Phys.-Acoust.	**Soviet Physics-Acoustics** *Akusticheskiy zhurnal*
Sov. Phys. J.	**Soviet Physics Journal** *Izvestiya vysshikh uchebnykh zavedeniy, Fizika*
Telecomm. Radio Eng.	**Telecommunications and Radio Engineering** *Electrosvyaz'*

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APPENDIX D

SOVIET AND EAST EUROPEAN RESEARCH FACILITIES CITED IN TEXT

(* Full information not available for all facilities)

Acoustics Institute im. N. N. Andreyev, AS USSR, Moscow
Akusticheskiy instiut imeni N. N. Andreyeva, AN SSSR/AKIN

Aerohydrodynamics Institute im. N. Ye. Zhukovskiy (Central), Moscow
Tsentral'nyy aerogidrodinamicheskiy institut imeni N. Ye. Zhukovskogo/ TsAGI

Aerological Observatory (Central), Dolgoprudnyy
Tsentral'naya aerologicheskaya observatoriya/TsAO

All-Union Cinematography Research Investigation Institute*

All-Union Electrical Machine Building Scientific Research Institute, Leningrad
Vsesoyuznyy nauchno-issledovatel'skiy institut elektromashinostroyenia/VNII Elektromash

All-Union Institute for the Improvement of Professional Skills for Leaders and Engineering Technical Workers in the Field of Standardization of Product Quality and Metrology*

All-Union Institute for Research on Current Sources for Construction and Technology Projects*

Applied Mathematics Institute im. M. V. Keldysh, AS USSR, Moscow
Institut prikladnoy matematiki imeni M. V. Keldysha, AN SSSR/IPM

Applied Physics Institute, AS USSR, Gor'kiy
Institut prikladnoy fiziki, AN SSSR/IPF

Atmospheric Optics Institute, AS USSR, Tomsk
Institut optiki atmosfery, SO AN SSSR/IOA

Atmospheric Physics Institute, AS USSR, Moscow
Institut fiziki atmosfery, AN SSSR/IFA

Automation and Electrometry/Electromeasurement Institute, AS USSR, Novosibirsk
Institut avtomatiki i elektrometrii, SO AN SSSR/IAiE

Aviation Engine Building Central Institute im. P. I. Baranov, Moscow
Tsentral'nyy institut aviatsionnogo motorostroyeniya imeni P. I. Baranov/TsIAM

Aviation Institute im. S. P. Korolev, Kuybyshev
Kuybyshevskiy aviatsionnyy institut imeni S. P. Koroleva/KAI

Aviation Institute im. Sergo Ordzhonikidze, Moscow
Moskovskiy aviatsionny institut imeni Sergo Ordzhonikdze/MAI

Aviation Institute im. A. N. Tupolev, Kazan'
Kazanskiy aviatsionnyy institut imeni A. N. Tupoleva/KAI

Aviation Institute im. N. Ye. Zhukovskiy, Khar'kov
Khar'kovskiy aviatsionnyy institut imeni N. Ye. Zhukovskogo/KhAI

Chemical Physics Institute, AS USSR, Moscow
Institut khimicheskoy fiziki, AN SSSR/IKhF

Civil Aviation Engineers Institute, Riga
Rizhskiy konstruktorno-inzhenernyy institut grazhdanskoy aviatsii/RKIIGA

Commercial Aeronautical Engineering Institute, Kiev*

Crystallography Institute im. A. V. Shubnikov, AS USSR, Moscow
Institut kristallografii imeni A. V. Shubnikova, AN SSSR

Dal'standardt Scientific-Industrial Union*

Derzhavniy University, Kiev, UkSSR*

Earth Physics Institute im. O. Yu. Shmidt, AS USSR, Moscow
Institut fiziki zemli O. Yu. Shmidta, AN SSSR/IFZ

Electrical Engineering Institute im. V. I. Lenin, Leningrad
Leningradskiy elektro-tekhnicheskiy institut imeni V. I. Lenina/LETI

Engineering Physics Institute, Moscow
Moskovskiy izhenerno-fizicheskiy insitut/MIFI

Experimental Meteorology Institute, Obninsk
Institut eksperimental'noy meteorologii/IEM

Far Eastern Scientific Center, AS USSR
Dal'nevostochenyy nauchnyy tsenter/DVNTs

Geophysics Institute, AS GeSSR, Tbilisi
Institut geofiziki, AN GeSSR

Gor'kiy State University im. N. I. Lobachevskiy, Gor'kiy
Gor'kovskiy gosudarstvenny universitet imeni N. I. Lobachevskogo

High Temperature Institute, AS USSR, Moscow
Institut vysokikh temperatur, AN SSSR/IVTAN

Hydrometeorological Institute, Prague, Czechoslovakia
Chesky hydrometeorologitsky ustav

Ionosphere Research Institute, AS USSR, Alma Ata
Institut issledovaniy ionosfera, AN KaSSR

Kaliningrad State University, Kalingrad
Kaliningradskiy gosudarstvennyy universitet

Karaganda Medical Institute, Karaganda
Karagandskiy meditsinskiy institut

Khar'kov State University im. A. M. Gor'kiy, Khar'kov
Khar'kovskiy gosudartsvennyy universitet imeni A. M. Gor'kogo

Kiev Polytechnic Institute (im. 50th Anniversary of the Great October Socialist Revolution), Kiev
Kiyevskiy politekhnicheskiy institut imeni 50-letiya velikoy oktyabr'skoy sotsialisticheskoy revolyutsii/KFI

Labor Hygiene and Professional Illness Institute, USSR Academy of Medical Sciences
Institut gigiyeny truda i professional'nyye zabolevaniya, AMN SSSR

Leningrad Institute of Motion Pictures Engineering*

Leningrad Mechanics Institute im. D. F. Ustinov, Leningrad
Leningradskiy mekhanicheskiy institut imeni D. F. Ustinova

Leningrad State University im. A. A. Zhdanov, Leningrad
Leningradskiy gosudarstvennyy universitet imeni A. A. Zhdanov/LGU

Makeyevskiy Engineering and Construction Institute*

Mathematics Institute im. V. A. Steklov, AS USSR, Leningrad (main branch in Moscow)
Matematicheskiy institut imeni V. A. Steklova, Leningradskoye otdeleniye, AN SSSR/MIAN

Moscow Energetics (Power Engineering) Institute, Moscow
Moskovskiy energeticheskiy institut/MEI

Moscow State University im. M. V. Lomonosov, Moscow
Moskovskiy gusudarstvenny universitet imeni M. V. Lomonosova

Moscow Technological Institute of Food Industries*

Oceanology Institute im. P P. Shirshov, AS USSR, Moscow (Kaliningrad), Gelendzhik, Lyublino
Institut okeanologii imeni P. P. Shirshova, AN SSSR/IOAN

Odessa Polytechnic Institute, Odessa
Odesskiy politekhnicheskiy institut

Pacific Ocean Oceanology Institute, AS USSR, Vladivostok
Tikhookeanskiy okeanologichesky institut, AN SSSR/TOI

Physical Technical Institute, Moscow
Moskovskiy fiziko-tekhnicheskiy institut/MFTI

Physical Technical Institute, AS UkSSR, Khar'kov
Khar'kovskiy fiziko-tekhnicheskiy institut, AN UkSSR/KhFTI (Ukrainskoy fiziko-tekhnicheskiy institut, AN UkSSR)

Physics Institute im. P. N. Lebedev, AS USSR, Moscow (affiliate in Kuybyshev)
Fizicheskiy institut imeni P. N. Lebedev, AN SSSR/FIAN

Polytechnic Institute im. Snechkus, Kaunas
Kaunasskiy politekhnicheskiy institut imeni Snechkusa

Problems of Mechanics Institute, AS USSR, Moscow
Institut problem mekhaniki, AN SSSR/IPM

Radio (Broadcast) Reception and Acoustics Scientific Research Institute im. A. S. Popov (A-U), Leningrad
Vsesoyuznyy nauchno-issledovatel'skiy institut radioveshchatel'nov priyema i akustiki imeni A. S. Popova

Radio Electronics Institute im. Yangel'ya, Khar'kov
Kharkovskiy institut radioelektroniki imeni Yangel'ya

Radio Engineering and Electronics Institute, AS USSR, Moscow
Institut radiotekhniki i elektroniki/IRE

Radiophysics Scientific Research Institute, AS USSR, Gor'kiy
Gor'kovskiy nauchno-issledovatel'skiy radiofizichesky institut, AN SSSR/NIRFI

Research Institute of Preventative Medicine, Bratislava, Czechoslovakia*

Sanitary Hygiene Medical Institute, Leningrad*

Semiconductor Physics Institute, AS USSR, Novosibirsk
Institut fiziki poluprovodnikov/IFP

Shipbuilding Institute, Leningrad
Lenigradskiy korablestroitel'nyy institut/LKI

Siberian Physical Technical Institute im. Kuznetsov, Tomsk (located at Tomsk State University
(Sibirskiy) fiziko-technicheskiy institut imeni Kuznetsova

State Scientific Research and Design Institute of the Rare-Metal Industry*

Steel and Alloys Institute, Moscow
Moskovskiy institut stali i splavov/MISiS

Terrestrial Magnetism, Ionosphere and Radio Wave Propagation Institute, AS USSR, Troitsk (affiliate in Leningrad)
Institut zemnogo magnetizma, ionosfery i rasprostraneniya radiovoln, AN SSSR/IZMIRAN

Terrestial Magnetism, Ionosphere, and Radio Wave Propagation Institute, (Siberian), AS USSR, Irkutsk
(Sibirskiy) institut zemnogo magnetizma, ionosfery i rasprostraneniya radiovoln, SO AN SSSR/SibIZMIR

Theoretical and Applied Mechanics Institute, AS USSR, Novosibirsk
Institut teoreticheskoy i prikladnoy mekhaniki, SO AN SSSR/ITiPM

Tomsk State University im. V. V. Kuybyshev, Tomsk
Tomskiy gosudarstvennyy universitet imeni V. V. Kuybysheva

Water Problems Institute, Moscow
Institut vodnykh problem

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APPENDIX E
FASAC REPORT TITLES
(* asterisk before title indicates report is classified)

(completed)

FY-82/83

* Soviet High-Pressure Physics Research
Soviet High-Strength Structural Materials Research
Soviet Applied Discrete Mathematics Research
* Soviet Fast-Reaction Chemistry Research

FY-84

Soviet Physical Oceanography Research
Soviet Computer Science Research
Soviet Applied Mathematics Research: Mathematical Theory of Systems, Control, and Statistical Signal Processing
Selected Soviet Microelectronics Research Topics
* Soviet Macroelectronics (Pulsed Power) Research

FY-85

FASAC Integration Report: Selected Aspects of Soviet Applied Science
Soviet Research on Robotics and Related Research on Artificial Intelligence
Soviet Applied Mathematics Research: Electromagnetic Scattering
* Soviet Low-Energy (Tunable) Lasers Research
Soviet Heterogeneous Catalysis Research
Soviet Science and Technology Education
Soviet Space Science Research
FASAC Special Report: Effects of Soviet Education Reform on the Military
Soviet Tribology Research
Japanese Applied Mathematics Research: Electromagnetic Scattering
Soviet Spacecraft Engineering Research
Soviet Exoatmospheric Neutral Particle Beam Research
Soviet Combustion Research
Soviet Remote Sensing Research and Technology
Soviet Dynamic Fracture Mechanics Research

(completed/cont.)

FY-86/89

Soviet Magnetic Confinement Fusion Research

Recent Soviet Microelectronics Research on III-V Compound Semiconductors

Soviet Ionospheric Modification Research

Soviet High-Power Radio Frequency Research

Free-World Microelectronic Manufacturing Equipment

FASAC Integration Report II: Soviet Science as Viewed by Western Scientists

Chinese Microelectronics

Japanese Structural Ceramics Research and Development

System Software for Soviet Computers

Soviet Image Pattern Recognition Research

West European Magnetic Confinement Fusion Research

Japanese Magnetic Confinement Fusion Research

* Soviet Research in Low-Observable Materials

FASAC Special Study: Comparative Assessment of World Research Efforts on Magnetic Confinement Fusion

FASAC Special Study: Defense Dependence on Foreign High Technology

Soviet and East European Research Related to Molecular Electronics

Soviet Atmospheric Acoustics Research

Soviet Phase-Conjugation Research

(in production)

FY-86/89

Soviet Oceanographic Synthetic Aperture Radar Research

Precision Timekeeping Research in the Soviet Union

Soviet Optical Processing Research

Soviet Satellite Communications Science and Technology

FASAC Integration Report III: Soviet Information Sciences

FY-86/89 West European Nuclear Power Generation Research and Development

* Radiation Cone Research

FASAC Special Study: Non-US Artificial Neural Network Research

FASAC Special Study: Soviet Low Observable/Counter Low Observable Efforts: People and Places

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